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Field testing did not indicate any significant difference existed between the results obtained by the AC from the Bison and the DC from the Geo-Recon or BPR instruments.

Fixed depth surveys were run using different profiling arrays. The 3-electrode Wenner array profiles did not produce useful data from the depth of interest. The gradient array was the fastest and could quickly locate horizontal anomalies. The 4-electrode Wenner array gave good depth definition and appears to give a greater amplitude of response to horizontal change.

Test lines run with the Bison indicate readings from wet and dry electrodes with and without balancing should not be mixed in the same profile or expanding spread.

The standard equipment Bison reels and stakes proved unsatisfactory and were replaced with the reels and stakes that came with the Geo-Recon.

Fixed depth traverses were successfully interpreted by means of profiles and by contouring, but the contours presented a more complete picture. The vertical electrical soundings were interpreted by empirical means and by the curve matching technique. The curve matching technique seemed to be more consistent with known facts.

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HIGHWAY RESEARCH REPORT

ELECTRICAL RESISTIVITY TECHNIQUES

FINAL REPORT

STATE OF CALIFORNIA
BUSINESS AND TRANSPORTATION AGENCY
DEPARTMENT OF TRANSPORTATION
DIVISION OF HIGHWAYS

TRANSPORTATION LABORATORY
RESEARCH REPORT
CA-DOT-TL-2102-1-73-35

Prepared in Cooperation with the U.S. Department of Transportation, Federal Highway Administration December, 1973

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STATE OF CALIFORNIA—BUSINESS AND TRANSPORTATION AGENCY

RONALD REAGAN, Governor

DEPARTMENT OF TRANSPORTATION
DIVISION OF HIGHWAYS
TRANSPORTATION LABORATORY
5900 FOLSOM BLVD., SACRAMENTO 95819

December 1973

Trans. Lab. No. 632102
FHWA No. F-7-91

Mr. R. J. Datel
State Highway Engineer

Dear Sir:

Submitted herewith is a final research report titled:

ELECTRICAL RESISTIVITY TECHNIQUES

Elgar Stephens, E.G. and Ronald Mearns, E.G.
Co-Investigators

Marvin McCauley, E.G.
Principal Investigator

Under the Supervision of
Raymond A. Forsyth, P.E.

Very truly yours,

JOHN L. BEATON
Laboratory Director

ACKNOWLEDGEMENTS

This project was conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration, under agreement No. F-7-91.

The contents of this report reflect the views of the Transportation Laboratory which is responsible for the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

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INTRODUCTION

The objective of this study was to investigate electrical resistivity equipment and techniques for potential application to highway problems.

Highway problems that were considered to be amenable to solution by the resistivity method were those relating to groundwater, materials site investigations, verification or extrapolation of seismic and borehole data and problems in areas where refraction seismic methods are not applicable.

The resistivity method is based on the resistance of soil or rock to the passage of an electrical current. A definition of electrical resistivity is specific resistance per unit area. It is then normally expressed as ohm feet or ohm meters. The general equation for resistivity is:

$$\rho = \frac{RA}{L}$$

where ρ = resistivity
R = resistance (E/I)
A = area
L = length

There are several standard electrode arrays that are commonly used to obtain resistivity values. Most of them use two current and two potential electrodes, but differ in their arrangement and the spacings between electrodes. A general equation for the determination of the apparent resistivity as measured by any electrode configuration is:

$$\rho_a = (2\pi R)\left(\frac{1}{\frac{1}{C_1P_1} - \frac{1}{P_1C_2} - \frac{1}{C_1P_2} + \frac{1}{P_2C_2}}\right)$$

where C_1P_1, P_1C_2, C_1P_2 and P_2C_2 refers to the distance between the respective current and potential electrodes.

The two configurations most commonly used for obtaining engineering data are the Wenner and the Schlumberger. In the Wenner configration the electrodes are equidistant and the equation reduces to:

$$\rho_a = 2\pi aR$$

where a = the electrode spacing.

For the Schlumberger configuration, the distance between the two potential electrodes is much less than the distance between each current and potential electrode. If the distance $C_1C_2=2a$, and the distance $P_1P_2=b$, then the equation for the apparent resistivity reduces to:

$$\rho_a = \pi R \frac{[a^2 - \frac{b^2}{4}]}{b}$$

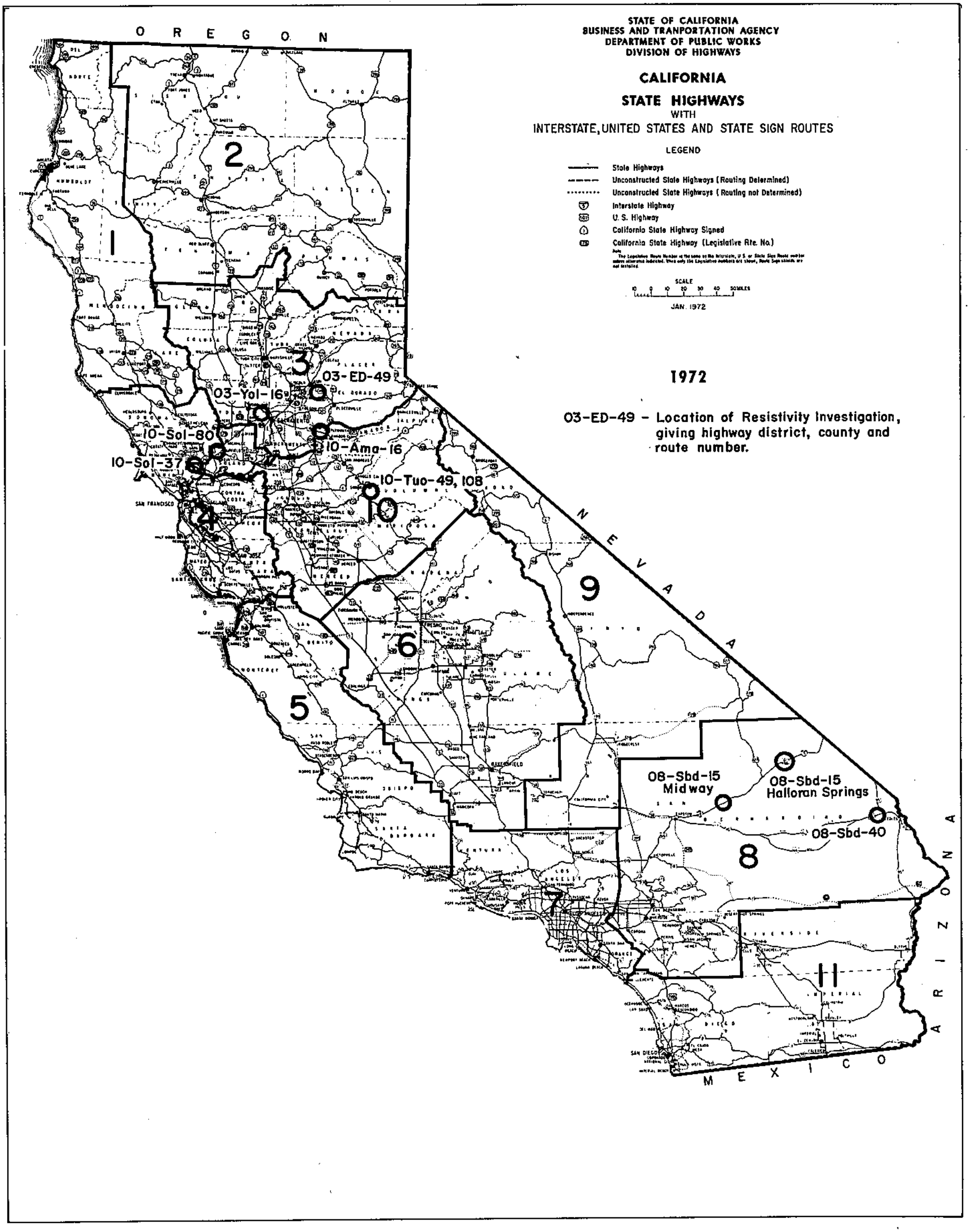
There are several different types of instruments available. These include those using direct current, commutated direct current, converted direct current and alternating current.

These were compared under both laboratory and field conditions. The first portion of the investigation was a study of the instruments in the laboratory to determine their capabilities or limitations and to determine possible sources of instrument error. The second was an extensive field test of the equipment. Factors evaluated and compared were equipment capabilities, operating conditions, power requirements, direct current versus alternating current power source, various probe arrays and different profiling methods.

Several different test sites were used because of the variety of tests that were conducted. Most of the sites were used several times in order to compare the effects of changes in soil moisture. The different sites are shown and identified on the state map in Figure 1.

The data were interpreted by different techniques which included curve matching and the cumulative method. The ease of applying these techniques and the accuracy of the interpretation are compared.

Figure 1


STATE OF CALIFORNIA
BUSINESS AND TRANPORTATION AGENCY
DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS
CALIFORNIA
STATE HIGHWAYS
WITH
INTERSTATE, UNITED STATES AND STATE SIGN ROUTES
LEGEND
State Highways
Unconstructed State Highways (Routing Determined)
Unconstructed State Highways (Routing not Determined)
Interstate Highway
U. S. Highway
California State Highway Signed
California State Highway (Legislative Rte. No.)
SCALE
JAN. 1972
1972
03-ED-49 - Location of Resistivity Investigation, giving highway district, county and route number.
OREGON
NEVADA
ARIZONA
MEXICO
1
2
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10
11
03-ED-49
03-Yol-16
10-Sol-80
10-Sol-37
10-Ama-16
10-Tuo-49, 108
08-Sbd-15
Midway
08-Sbd-15
Halloran Springs
08-Sbd-40
SAN FRANCISCO
BAKERSFIELD
SAN DIEGO

CONCLUSIONS

The Bison Instrument was the easiest and fastest to use. Although it could not accurately measure very small values of voltage or current, it was very accurate when measuring known resistances that were not extreme.

A permanent grounding terminal should be installed to discharge static buildup on the aluminum face. The cables and reels that are standard with the Bison instrument were not acceptable for field use.

The Geo-Recon can accurately measure the value of a known resistance and resistances over a wide range. The cables and reels that came with the instrument were the best of those used, but required improvement to prevent the reels from seizing on the axles.

The BPR Instrument is limited to resistivities in the mid range. This instrument often gave an erroneous reading of the actual resistivity, particularly if a scale change was made during the course of a survey.

None of the instruments could perform satisfactorily over conditions of extreme soil resistance.

At the depths involved in engineering investigations there was no detectable difference between direct current and the alternating current provided by the Bison.

Wetting the ground around the electrodes reduces the difference in contact resistance between different electrodes.

The gradient array is the fastest for locating horizontal anomalies.

Data from expanding spreads plotted on log log paper emphasize any scatter which makes it simpler to identify that which is undesirable.

The most dependable method of interpretation was the curve matching technique. Contouring of subsurface resistivity values from fixed depth profiles provides an additional tool that is very helpful in interpreting the profiles.

RECOMMENDATIONS

The BPR instrument should be considered outdated, and no longer satisfactory as a field instrument.

When there is a difference in the contact resistance between electrodes on a given survey, the contacts should be watered in order to reduce that variable to a minimum.

In order to obtain the most suitable curve for use with the curve matching technique, resistivity data should be plotted on log log paper as they are collected.

The resistivity data should be interpreted by the method of curve matching, preferably using a computer to corroborate the interpretation.

Additional work is required using the Schlumberger array, particularly in the drier areas of the state.

IMPLEMENTATION

The findings of the study have resulted in several changes in both data collection procedures and in the interpretive procedures used by the Transportation Laboratory.

Personnel of the Geophysical Unit of the Foundation Section no longer use the BPR instrument. As a result of this change, metal stakes rather than porous pots are used as the electrodes.

Water is poured around the electrodes whenever there seems to be any variation in contact resistance between electrodes.

The vertical soundings are expanded using a logarithmic rather than a linear expansion. Data are plotted as collected on log log paper. Interpretation of the field curves is by the curve matching technique and the interpretations are verified by use of a computer program.

Horizontal discontinuities are first located by means of gradient profiles. Expanding spreads are then run as necessary to determine depths.

In addition, these changes have been incorporated into the manual for the Transportation Laboratory in-service training course "Materials Considerations in the Planning, Design, Construction, Operation and Maintenance of Transportation Facilities". They will be included in the next edition of the Materials Manual on Exploration, Testing and Analysis Procedures (Vol. VI).

TESTING PROCEDURES

Because of the large number of variables, procedures, and methods investigated in this study, it is convenient to describe them according to the procedure followed in testing for each purpose.

The initial part of the study consisted of a laboratory study of the three instruments in which possible instrumental error and equipment capabilities were investigated. Other factors such as operating procedures, capabilities, power requirements, optimum operating conditions and field sources of instrument error were evaluated in the field.

Field tests were also conducted to evaluate surface resistivity conditions, direct current versus alternating current, various probe arrays and different profiling methods.

RESISTIVITY INSTRUMENTS

The three instruments used in the study were the Bureau of Public Roads design of 1936, which had been fabricated in our laboratory shops in 1957, the Bison Model 2350A and the Geo-Recon Model ER2. The BPR and Geo-Recon are direct current instruments while the Bison uses DC which is converted electronically to square wave alternating current.

Bureau of Public Roads Instrument

The measuring circuits of the BPR instrument consist of a potentiometer capable of measuring between .001 and 1.1 volts in ten steps, and a milliameter capable of measuring from .001 to .3 amps in 4 steps. The galvanometer is balanced against a standard cell. Power is supplied by an external battery box. The cables and reels are mounted on a carrying case with the current flow to the cables being through the reel itself. Metal stakes are used for the current electrodes and porous ceramic pots for the potential electrodes. The instrument case is of wood with dimensions of 7x9x20 inches.

Bison Model 2350A

The Bison Model 2350A is a self-contained transistorized instrument which electronically converts direct current to square wave alternating current. The instrument is shown by Figure 2. Input current to the ground is limited to a maximum of .025 amps. Input voltage is 540 volts, peak to peak, supplied by three 90 volt batteries. Functional operation of the instrument can be checked along with battery condition by means of a test position on the potential electrode selector switch. In the test position, the external cables are disconnected and a standard load is connected across the instrument internally.

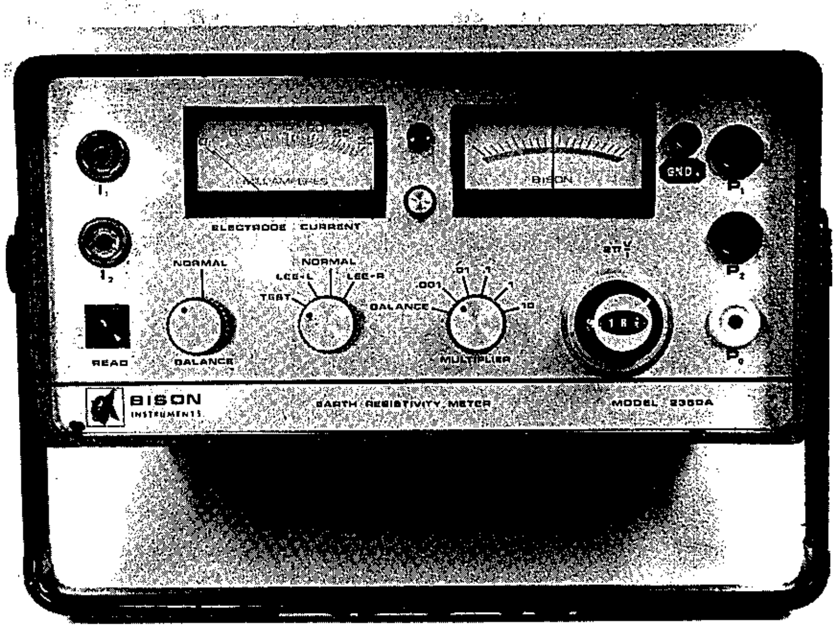


Figure 2. Bison resistivity meter.

A switch must be depressed before current flows through the circuit. This guards against shock and extends battery life. The reading dial is rotated until the null meter is balanced and the value is then read from the drum type dial within the knob. The reading is given as the product of $2\pi R$. An electrode balance provides for balancing the potential electrodes when using the .001 multiplier scale.

The normal input impedance of the potential measuring circuit is very high and appears in shunt with the contact resistance of the potential electrodes. High contact resistance at the potential electrodes will therefore reduce the measured voltage by a slight amount. A means is provided to reduce the input impedance of the potential electrodes by one-half when high contact resistance is creating a problem in the potential circuit. Nominal frequency of the instrument is 11 Hertz, but can be adjusted to plus or minus 15% by means of the frequency adjustment control.

The instrument is contained in a plastic case that measures 6x12x10 inches.

The stakes and reels that came with the Bison were of a poor design which caused a number of problems. Each electrode is constructed with a cross bar which serves the purpose of holding the reel containing the wire. Electrical contact from the cable is through the reel itself. Figure 3 shows two of the reels on the crossarms of two of the stakes.

The stakes were of too large a diameter to be easily driven into hard ground. The force required to drive them into the ground frequently caused the cross arms to break off. The reels were of aluminum with a hollow tube spot welded in the center to fit over the cross arm. After a relatively short time the spot welds broke, causing poor electrical contact. The reels were also barely large enough to hold the wire. New reels and new stakes were fabricated to replace the originals. The replacements were not wholly satisfactory since there was still a high incidence of failure of reels, stakes and wires, requiring greater effort by field personnel (a four pound hammer was required to drive the stakes). The wires became twisted and then broke. Poor contacts between the reels and stakes often required extra walking between electrodes to obtain good current flow. The problem was solved by using the Geo-Recon reels and stakes with both the Bison and Geo-Recon instruments.

Another problem that caused considerable difficulty was a buildup of static electricity on the metal face of the instrument. The charge affected the meters causing them to give erroneous readings. This appears to have been solved by installing a grounding circuit between the instrument face and earth.

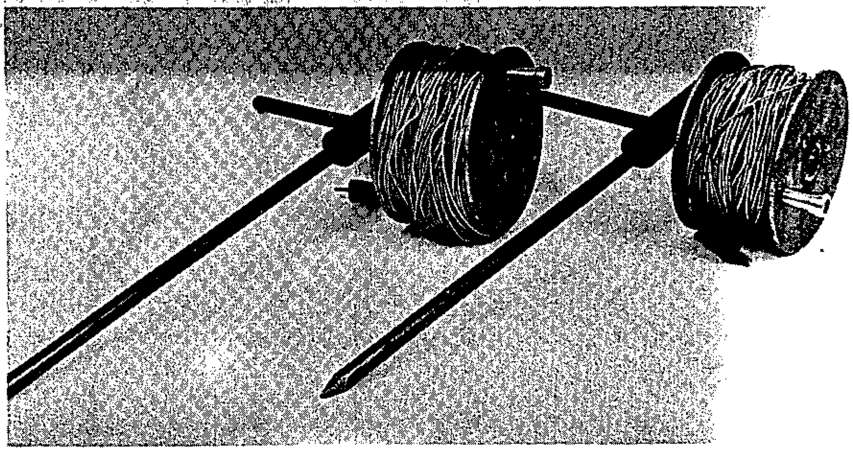


Figure 3. Two of the Bison stakes shown with the reels on the crossarms. These reels and stakes are the replacements fabricated in our shops.

Geo-Recon Model ER2

The Geo-Recon Model ER2 was manufactured by Geo-Recon (now Slope Indicator). The instrument was designed partially on the basis of a prototype built for their own use and partially according to specifications supplied by this department. It is completely self-contained, fully transistorized and utilizes low power FET operational amplifiers and integrated circuits. The voltmeter ranges are from .01 to 100 volts in five steps with a resolution of .0001 volts. Current output ranges from .0001 to 1 amp in four steps with a resolution of 10 microamps. A neutralizer circuit allows precise correction of natural DC ground currents or current from electrolysis in the voltage circuit. This circuit makes it possible to use metal stakes in place of porous pots for the potential electrodes. A stake configuration switch allows the instrument to be used for either the Wenner or Lee partitioning method. Power is supplied by four internal 45 volt B batteries. The instrument is mounted in a 14x9x11 inch Halliburton case and is shown in Figure 4.

The cable reels are mounted on a packframe as shown in Figure 5. Current is transmitted through the reels to the stakes by carbon brushes riding on a brass shaft inside the nylon cores of the reels. Drag for the reels is provided by brass lock washers being compressed against the bottom of the nylon core. A grounding circuit for the instrument, or for the Lee partitioning method, is provided through the interconnect cable and a terminal on the pack frame.

Several hours of lost field time were also caused by these reels which have a nylon bushing and turn on a bronze shaft. It appears that dust causes a burr to form on the bronze shaft, which digs into the nylon bushing and causes the reel to freeze. This happened many times and usually took an hour or so to repair. The best preventative thus far has been to lubricate the shaft with an electrical contact cleaner.

The neutralizer circuit in this instrument had an intermittent short that persisted for 2 of the 2-1/2 years we have had the instrument. During this time it was returned to the factory twice for repair. It was finally corrected by Laboratory personnel after the problem had caused the instrument to become inoperative on six different field trips. The trouble was determined to be intermittent contact between a diode and the solder which had flowed around but was not adhering to the wire.

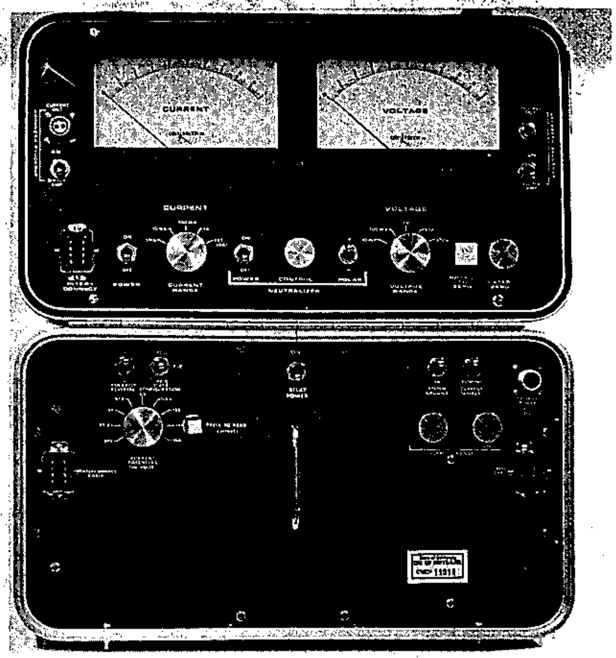


Figure 4. Geo-Recon resistivity meter.

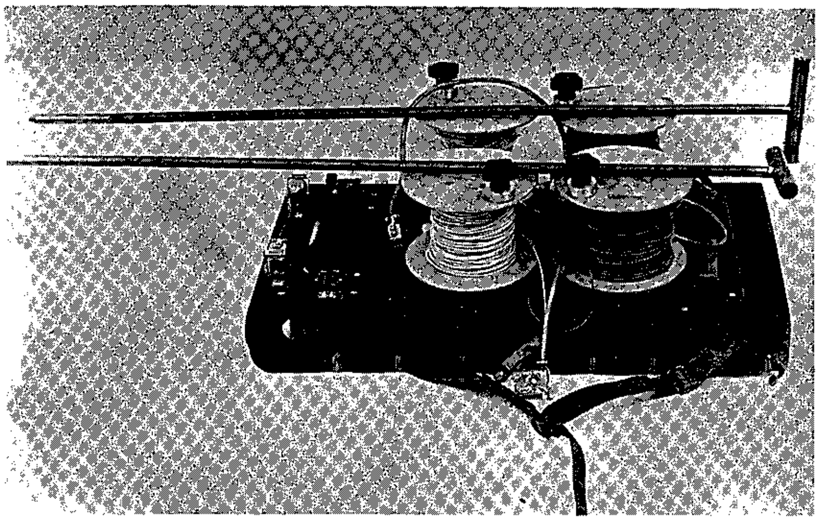


Figure 5. Geo-Recon reels on the packboard which also serves as a mounting frame. Two of the copper stakes are shown lying across the reels.

LABORATORY TESTS

On numerous occasions in the past, field readings could not be obtained with the BPR instrument. A laboratory study of the instrument was considered necessary to determine the source of the problem. At the same time the study was extended to include the other two instruments.

The procedure used resistors to simulate the earth which permitted a determination of the limitations of each instrument. Results of this investigation revealed the BPR instrument does not have a built-in resistor to limit current flow to the ground. Consequently sufficient soil resistance is required to limit the current flow to .3 amps, the maximum reading on the meter. At the same time, the resistance between the two potential electrodes must not develop more than 1.1 volts, the maximum reading on the potentiometer.

The tests were performed using a 6 volt battery as the power supply and resistors of 10% accuracy. Previous experience had indicated that under conditions of low resistivity, field readings could not be obtained using the 22.5V battery. Under such conditions a reading could usually be obtained using a 1.5V battery.

The first test resistor circuit is shown in Figure 6. With this configuration the only resistor in the circuit was R2. An R2 could not be found that would give values for both E and I that were on scale. Tests with a variable resistor demonstrated that the minimum total resistance between C_1 and C_2 must be 25Ω to keep the current reading on scale. With this particular configuration, 25Ω at R2 would drive the voltage meter off scale. Apparently, the nominal 6 volt battery being used was only producing 5.5 volts for this test. The second test was with two additional resistors in the circuit as shown in Figure 7.

A test was then made using R1 and R3 of 15Ω each and R2 of 3.75Ω, which gave readings of I=.246 amps and E=.704 volts. Considering the precision of the resistors, R2 should have been read as being between 3.28 and 4.12Ω, not 2.86 as given by .704/.246.

If the impressed voltage were increased to 22.5 volts there would have to be a corresponding increase in resistance to keep the amperage meter on scale. However, if the resistance becomes very high, as would be expected in desert conditions, the high resistance would drive the voltage meter off scale. This test seemed to indicate the instrument can only be used over a limited range of field conditions. This observation was borne out by field use.

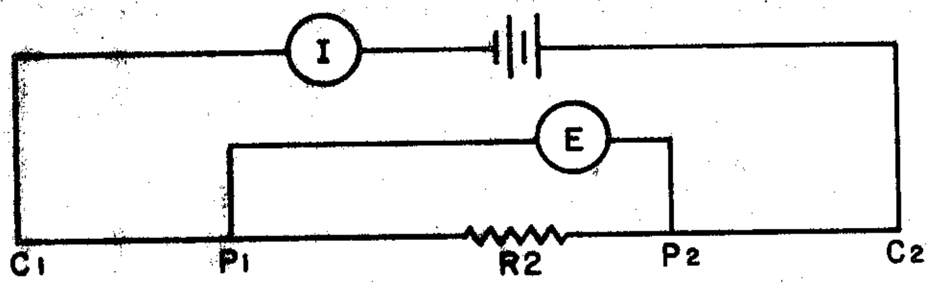


Fig. 6. Schematic of Resistivity meter connected to test apparatus with one resistor in the circuit.

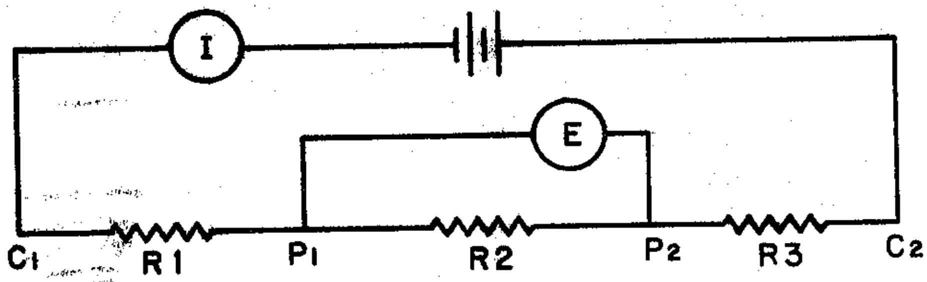


Fig. 7. Schematic of Resistivity meter connected to test apparatus with three resistors in the circuit.

The Bison instrument was then tested on the same resistor arrangement. It gave accurate values for the resistor R2, and because current flow is limited to .025 amps, it could give readings for all the resistors used.

The Bison can often give an apparent resistivity value for a given situation on more than one scale. Tests were conducted to determine if these different apparent resistivities from different scales gave the correct value for known resistors. These tests determined that the different readings were not always the correct value. The scales are not linear at their extreme ends and tend to give incorrect values at these extremes. Also, the reading with the most significant numbers showing on the dial tends to be the most accurate.

A set of testing resistors was assembled for testing the various scales. The testing resistors had values of .8, 8, 80 and 800 ohms, with an accuracy of plus or minus 1%. The respective readings of $2\pi E/I$ for these resistors was 5.02, 50.24, 502.4 and 5024.0. Figure 8 shows a picture of the test resistors mounted in plastic and equipped with test jacks. The testing device is carried with the instrument and used periodically to check its performance.

The Geo-Recon instrument was then tested with the same resistor arrangement as used with the other instruments. There was no problem in getting readings with any of the resistors. It was also determined experimentally that the readings gave a very accurate value for any resistor R2.

This instrument is limited in current flow at each scale setting to the maximum value of that scale. During one test, stray current from the 110V circuits in the laboratory created interference which was easily cancelled by the neutralizer circuit.

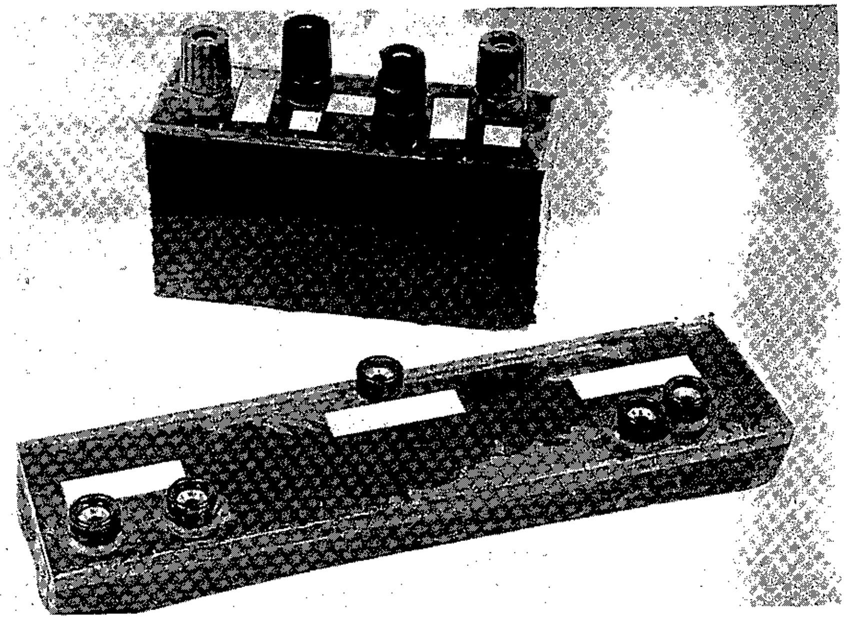


Figure 8. Test resistors mounted in plastic. These "artificial earths" are carried with the instruments and used as calibration or operational tests.

FIELD TESTS

The field tests were usually a comparison between different instruments and equipment, or different procedures. The procedures compared were different electrode configurations, use of the instruments with and without the neutralizer circuits, application of water to the ground around the electrodes, and different soil moisture conditions.

The two basic methods of obtaining data were the profile and the expanding spread. The electrode configurations used for the profile or constant depth surveys were the 4-electrode Wenner, 3-electrode Wenner and the gradient array.

The electrode configurations used for the expanding spread or vertical electrical sounding (VES) method were the Wenner and the Schlumberger arrays. The Wenner array was given extensive testing, but only limited testing was done of the Schlumberger array. A long delay in obtaining delivery of the Schlumberger master curves prevented us from using the curve matching technique for interpreting Schlumberger data. Since this was considered to be the only acceptable technique, no interpretation could be made until the curves were obtained.

The 4-electrode Wenner is the standard Wenner array. For profiling purposes, it is advanced along a traverse using a constant "a" spacing. The 3-electrode Wenner is very similar, except that one current electrode remains stationary at the end of the traverse.

The gradient profile has both current electrodes stationary, and separated a distance that can be considered as infinite. For practical purposes, this "infinity" can be from ten to twenty times the separation of the two potential electrodes. The two potential electrodes can be moved anywhere within approximately the middle one-third of the separation between the current electrodes. Moving them too close to either current electrode will distort the gradient upwards toward that current electrode. This array can be used to cover a large area rather quickly, since lateral movement is also possible. When horizontal anomalies are located, an expanding spread is then necessary to determine depths.

Resistivity profiles were run at a number of different locations. These can be divided into two classes, depending on whether the geology is simple or complex. In the areas of simple geology a total of 50 profiles were run, of which 22 were gradient array, 24 were Wenner array and 4 were 3-electrode Wenner. Useful information was obtained from 18 of the gradient, 9 of the Wenner, and none of the 3-electrode Wenner. No information was gained from 3 gradient, 8 Wenner or any of the 3-electrode Wenner arrays.

In the two areas of more complex geology, a total of 75 Wenner and 61 gradient profiles were run. All of these appear to have provided data that was useful, though not for the intended purpose. The intended purpose was the location of cavities, but the geologic complexity of the areas created more anomalies than background. Consequently, definite statements about the source of each anomaly were impossible. The general geology does appear to have been delineated according to the know conditions.

The gradient array is considerably faster to use in the field since only half as many electrodes must be moved. This array does not give much depth resolution, but does quickly locate horizontal anomalies.

The Wenner array is slower to use, but gives good depth definition, and appears to give a greater amplitude of response to horizontal changes. It is therefore a better array to use when the changes are more subtle.

The 3-electrode Wenner array seemed to be so sensitive to changes in surface resistance that it did not show useful data from the depth of interest.

The first test of the BPR instrument was at the site along RD 10-Ama-16. The ground was dry on the surface but had moisture at a depth of a few inches. A gradient profile was used with twenty feet between the potential electrodes and the current electrodes were well watered. The plotted data were later compared to an identical profile run with the Bison instrument. The plotted profiles are essentially parallel, with the same major features, although the resistivity values were significantly different. There are many minor irregularities on the profiles that could be attributed to data scatter, but with the trend of the BPR profile being somewhat smoother than the trend of the Bison profile.

The twenty foot gradient profile was then continued across a cavity at a known depth of fifteen feet, using both instruments. The cavity would have been located on the evidence of the Bison profile, but not on the evidence of the BPR profile. There were several sharp inflections on the BPR profile, including one over the cavity; but, because of data scatter, it was not possible to identify any one inflection as being proof of a cavity.

A ten foot gradient profile was run at this same location when the ground was very wet. Reproducibility of the BPR readings was poor, but the plotted profile was reasonably smooth - until it was necessary to change scales. Changing scales displaced the curve by a factor of almost ten. In order to finish the profile it was necessary to make changes in the input voltage so that no scale changes were required. The poor reproducibility of the instrument was attributed to the very low voltage at the location and the inability of the potentiometer to correctly indicate such small voltages. The smallest values that can be read directly from this instrument are one millivolt or one milliamp.

Tests of the Bison instrument were also made at the 10-Ama-16 location at the same time as the BPR instrument was being tested. At the time of the first tests, the ground was very wet, and resistance was low. A gradient profile was attempted with spacing of ten feet between the potential electrodes. The values given by the instrument were very small, and not reproducible. The values had a range as shown below.

Station	Instrument Reading ($2\pi R$)
0	.042 - .046
10	.038 - .041
20	.021 - .0306
30	.0204 - .026
40	.0204 - .033

The Bison instrument has a built-in limitation on current flow of .025 amps. Under conditions of very good current flow such as this, the value was a constant at .0235 amps. The only variable was the voltage drop between P_1 and P_2. The calculated voltage drop for these readings are as follows:

$2\pi R$	Voltage Drop
.042 - .046	.000157 - .000172
.038 - .041	.000142 - .000153
.021 - .0306	.000078 - .000114
.0204 - .026	.000076 - .000097
.0204 - .033	.000076 - .000123

Normal operating procedure for this condition would be to change the voltage or current input until the voltage drop between the potential electrodes could be more accurately read. Since the input is not adjustable on this instrument, that procedure was not possible.

The profile was not completed as the voltage drop was considered to be less than the discriminating ability of the instrument. Had the profile been completed, the data could probably have been made usable by plotting it on a subdued scale.

The next test of the Bison at this site was some time later when the ground was relatively dry on the surface but moist at a depth of a few inches. This test was for the purpose of observing the effects of contact resistance and to evaluate the ability of the instrument to balance out the effects of electrolysis. The array was a 20 foot gradient profile with the two current electrodes placed at infinity and well watered. Readings were taken first with dry potential electrode contacts and then again after watering around the contacts. The entire line was run this way, using the .001 scale without balancing the null meter. The line was then repeated using first dry then wet contacts, but with the null meter balanced before each reading. The four sets of data were then plotted as four profiles which are shown in Figure 9. There was considerable difference in value under the different conditions. The results are somewhat inconclusive, but the wet, balanced readings form the smoothest profile and sharpest anomalies. From this, we can conclude that such different readings should not be mixed in the same profile or expanding spread. If, as has been claimed, wetting the ground around an electrode creates a variable resistor in series with the circuit, not wetting it probably makes the resistor even more variable.

These records also show the differences in results obtained when the balancing procedure is not used, and point out the need for balancing prior to each reading on the .001 scale.

Another test of the Bison instrument was made at the same location approximately one month later when the ground was dry. For this test, three Wenner profiles were run taking two readings at each electrode station. The only difference between the two readings was the scale multiplier used. The results are summarized below. All three lines used the Wenner array profiling technique.

10 Foot "a" Spacing (Fig. 10).

Data read using the .1x, 1x and the 10x scale on one end of the line. The .1x and 1x readings were parallel but approximately 6 ohm feet apart. On the one end where the 1x and 10x were used, the readings were parallel but approximately 40 ohm feet apart.

20 Foot "a" Spacing (Fig. 11).

Data read using the .1x and 1x scale multipliers. The values are parallel and approximately 10 ohm feet apart.

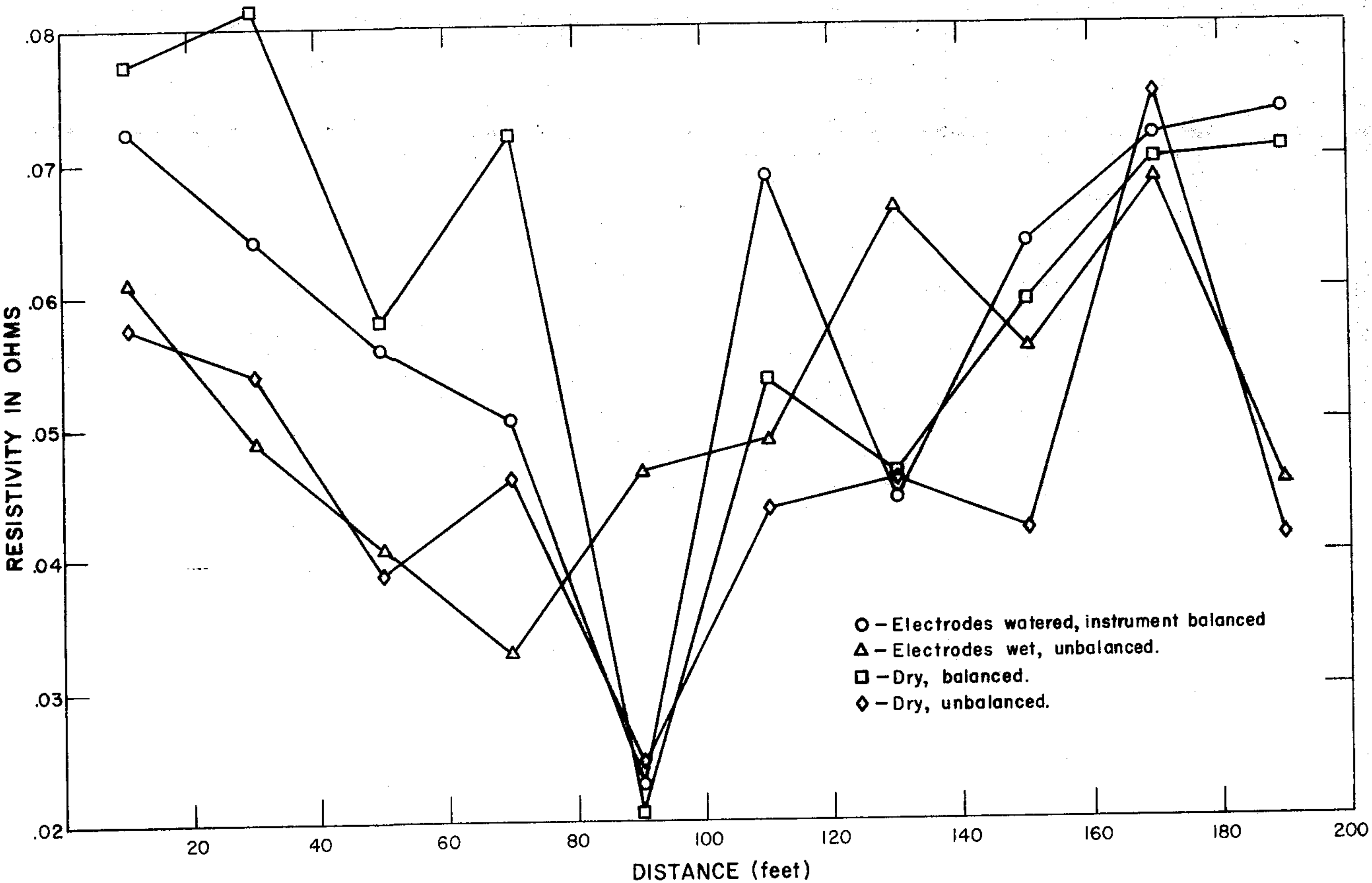


Figure 9. Four gradient profiles at the same location with the Bison instrument. The graph shows the results of the use or non-use of the balancing circuit and of wet or dry electrodes.

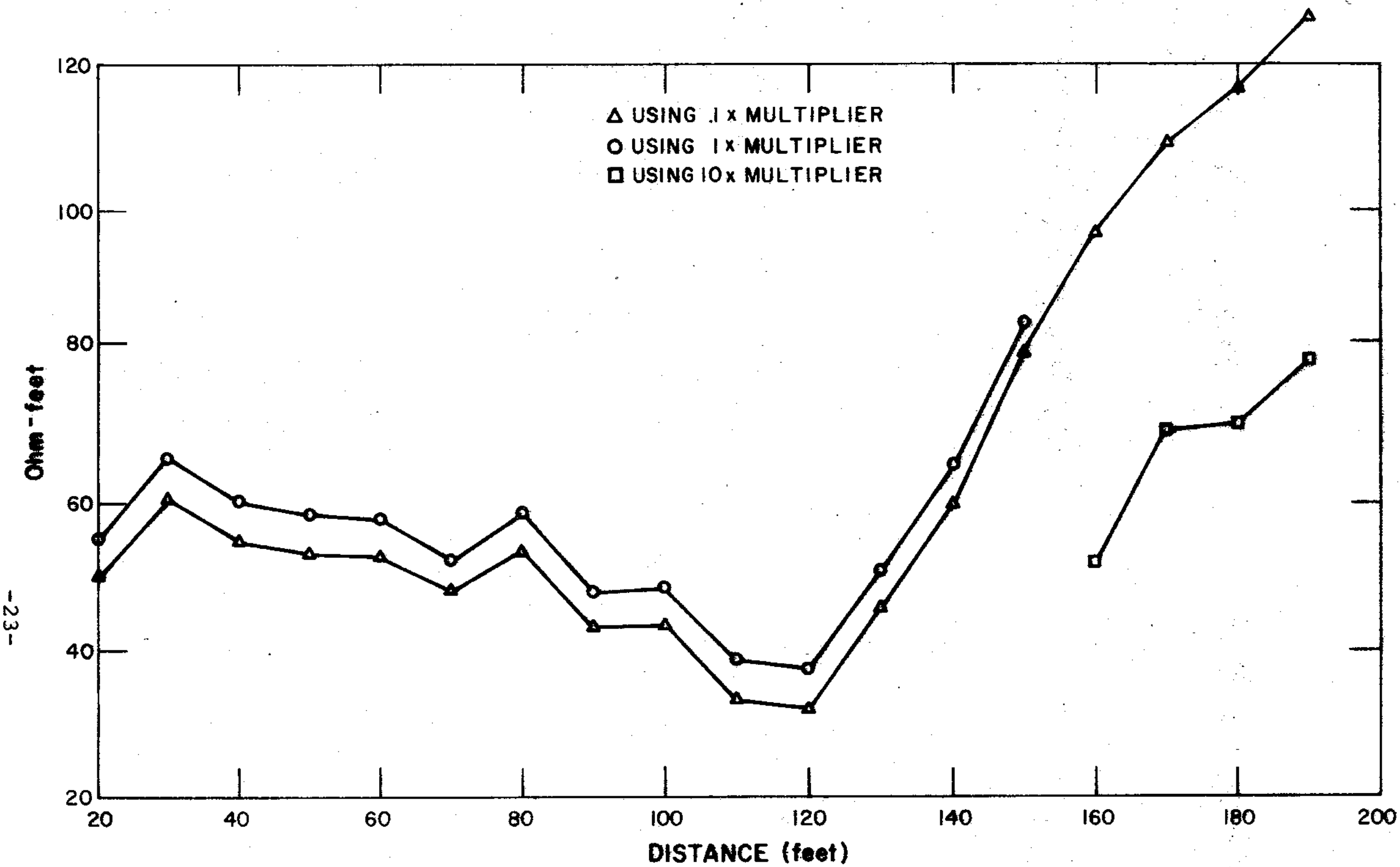


Figure 10. Resistivity profile run with the Bison instrument using a Wenner array with 10 foot "a" spacings. Two readings were obtained at each station, using different scale settings.

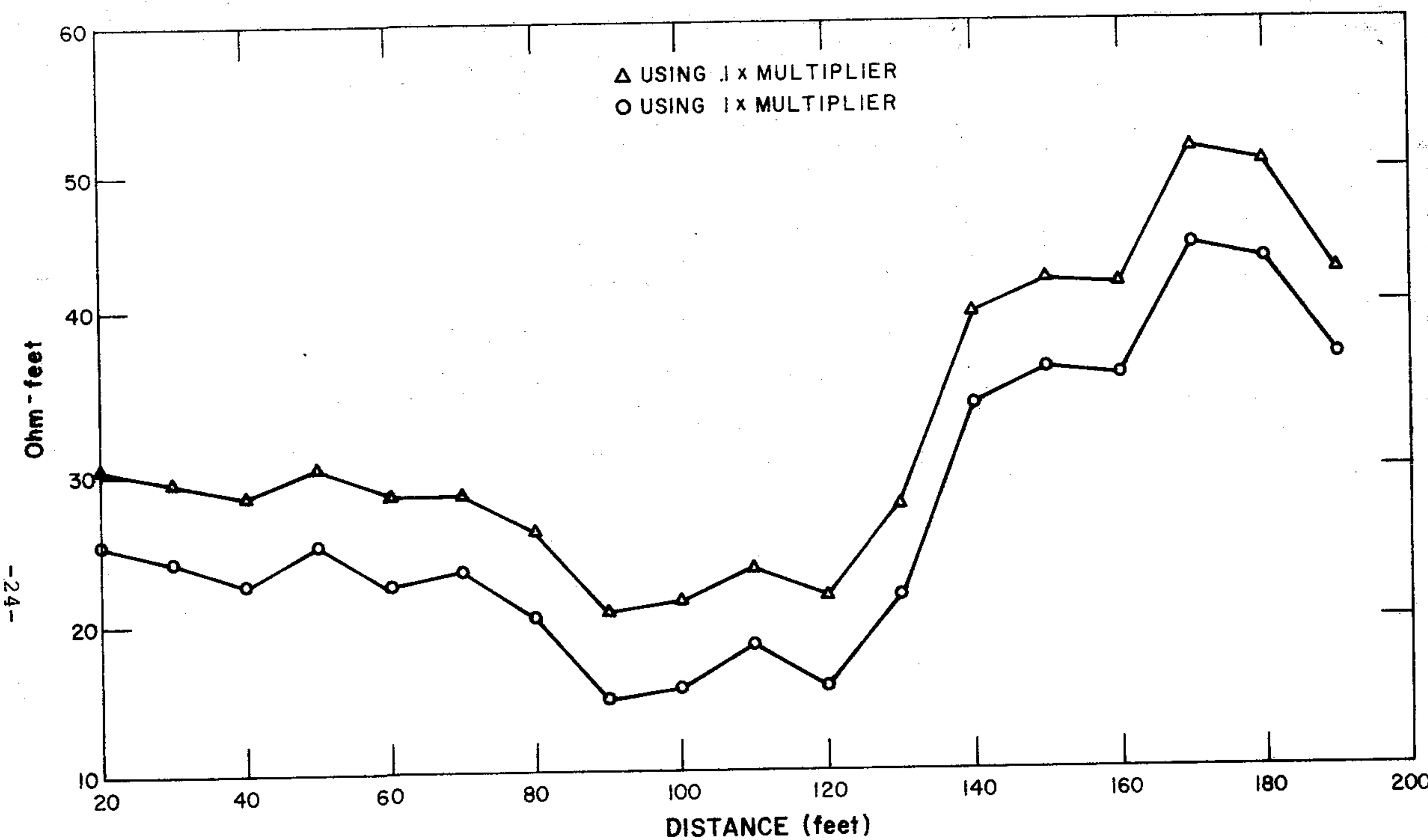


Figure 11. Resistivity profile run with the Bison instrument using a Wenner array with 20 foot "a" spacings. Two readings were obtained at each electrode position, using different scale settings.

30 Foot "a" Spacing (Fig. 12).

Data read using the .1x and 1x scale multipliers. The values along two-thirds of the profile are parallel but 10 ohm feet apart, and along the other one-third the values are the same. The overlaid interval is in the mid range of the recorded values.

Another field test of the Bison was at American Canyon at a time when the surface was moist and contact resistance not too high. A gradient profile was attempted using a P_1P_2 distance of 20 feet and an infinity of 440 feet. This arrangement did not generate enough voltage drop between the two potential electrodes for the instrument to give usable readings. A Wenner profile was then run at the same location using an "a" spacing of 20 feet.

Rain began falling while the profile was in progress and enough leaked through the face of the instrument to cause internal shorting, necessitating a return to the Laboratory for repairs. A subsequent trip to the same area was then made to collect data from additional expanding spreads. None of these expanding spreads could be expanded to a sufficient length to get good definition of the subsurface. The maximum "a" spacings that could be used varied from 50 to 100 feet, depending on the exact location at the site. Beyond these distances the null needle began pulsing and the values given were extremely high and obviously erroneous. Figure 13 shows an example of one of these lines. There were two high voltage power lines in the immediate vicinity which, it was thought, might be affecting the instrument.

The same phenomenon occurred several months later in the Yolo Bypass area. At this location there were also power lines nearby, a moderate wind was blowing and the ground was generally dry. At the time of this second occurrence it was observed that passing ones hand over the meters caused the needles to deflect, and that the null meter did not seem to be responding properly. A grounded wire brought into contact with the aluminum face of the instrument caused an apparent static discharge. A permanent grounding terminal was then installed to ground the aluminum face.

Another test of this phenomenon was made on Mare Island. At this site there were also power lines and a stiff breeze, although the ground was very wet. A Wenner profile was being run, using the grounding terminal and getting readings of approximately .07 to .08. With the ground disconnected the reading jumped to 1.5. Reinstalling the ground caused the readings to return to the .07 to .08 level.

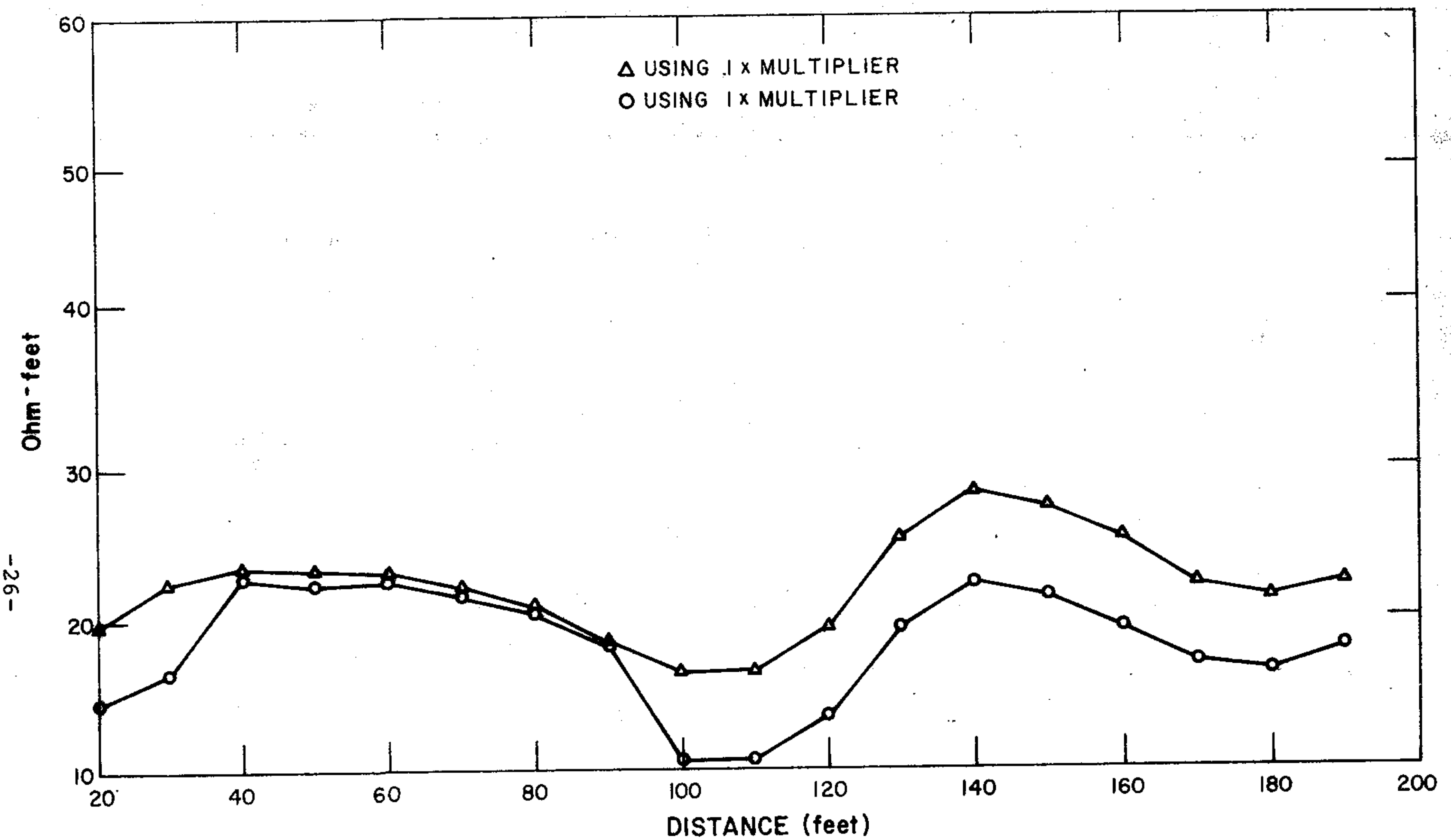


Figure 12. Resistivity profile run with the Bison instrument using a Wenner array with 30 foot "a" spacings. Two readings were obtained at each electrode position, using different scale settings.

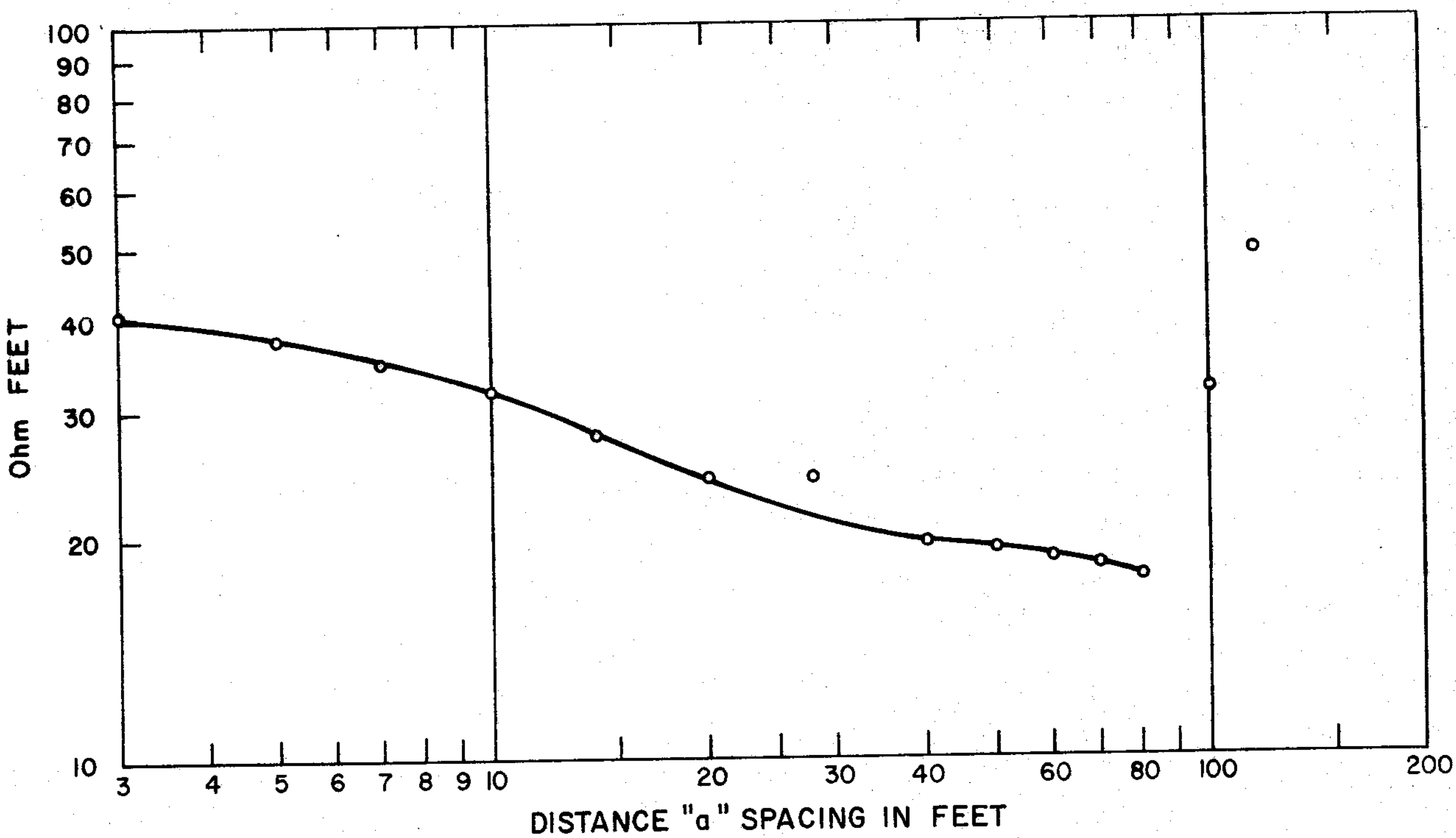


Figure 13. A field resistivity curve from American Canyon, showing the effect of "interference" on the Bison instrument.

A follow-up check on the effectiveness of the ground was later made at the American Canyon site. The attempt was unsuccessful since the instrument did not behave as it had on the other occasions. On this trip, good Wenner array expanding spread data were collected until the "a" spacing reached 90 feet. Beyond 90 feet, the data were badly scattered either with or without the ground connected. Figure 14 illustrates the data scatter.

The Bison and the Geo-Recon instruments were compared at a number of different sites. One of these comparisons was at the 10-Ama-16 site. The test was a Wenner profile by each instrument using the same electrode stations. The two sets of data were then plotted on a single sheet to facilitate comparison. Except for one reading where the two lines cross, they remain parallel and about 6-10 ohms apart. The two lines are shown in Figure 15.

A field test conducted at Halloran Springs Rest Stop in November 1970 also compared the performance of the Bison and Geo-Recon instruments. This was a test of not only contact resistance but of near surface soil resistance as well. It was not possible to get any current flow on either instrument without wetting the ground around the electrodes. Even when the ground had been watered current flow on the Bison was usually low, always variable and sometimes less than .005 amps. The Geo-Recon was usually operated at full power of 180 volts, and sometimes had a current flow low enough to require use of the .010 amp scale. The performance of both instruments would have to be rated as poor to unsatisfactory with much scatter and poor reproducibility.

The same area was surveyed again in January 1971 after a December rain. The surface was dry but there was moisture at a depth of 3-4 inches. The only instrument used this time was the Geo-Recon. Impressed voltage was never higher than 112, usually between 67 and 90 volts. The performance was very good with little data scatter.

Another attempt to compare the performance of the Geo-Recon and Bison was made at the Midway Rest Stop in January 1972. The ground was completely dry and contact resistance very high. The survey was begun using the Geo-Recon, which failed after three readings and could not be used again. The Bison was then used to collect data from two Wenner expanding spreads. The data were good to an "a" spacing of 140 feet, but badly scattered beyond that.

By the time the equipment could be returned to the field in February, it had rained and the soil was no longer relatively dry. Because of scheduling problems, only the Geo-Recon was used on this second trip. The first line was a repeat of one of those

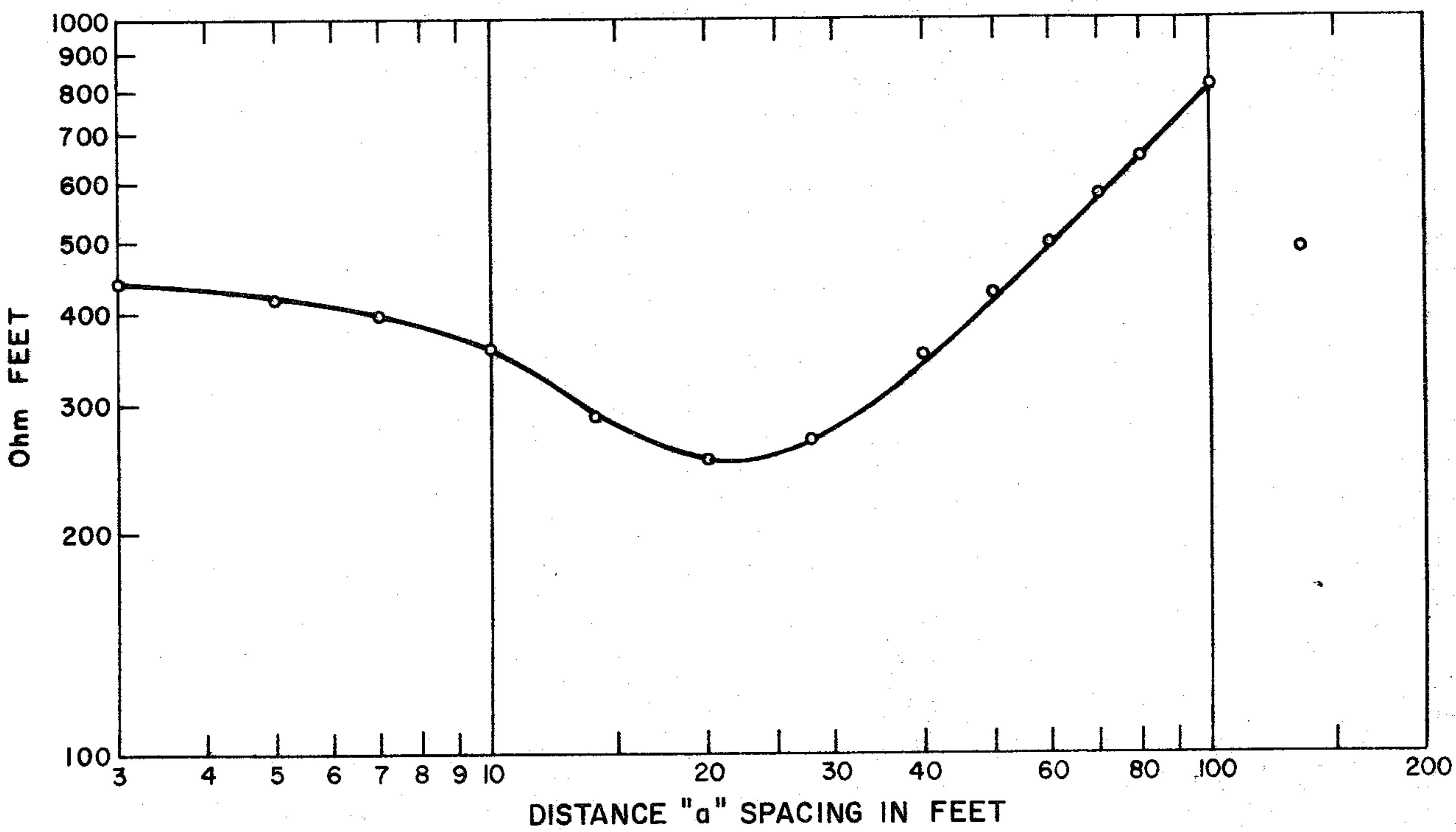


Figure 14. A field resistivity curve obtained near the site of Figure 13 in American Canyon. This line has good data to an "a" spacing of 100 feet, with wide scatter beyond that distance.

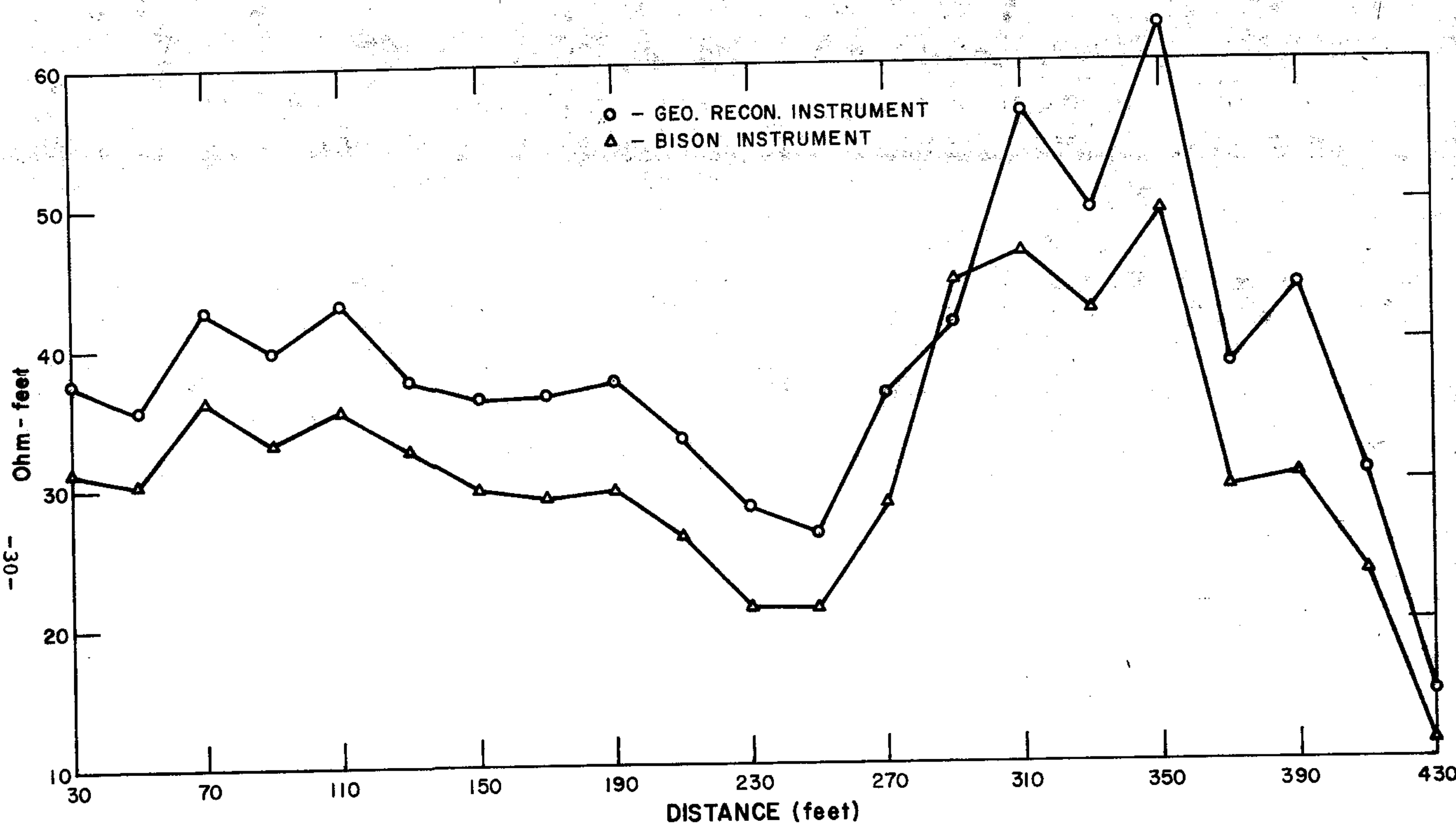


Figure 15. Two Wenner profiles obtained at the same location with the same cables, electrodes and electrode positions, but with two different instruments.

run with the Bison in January. It was started with an "a" spacing of 100 feet and expanded to 600 feet. The result was a smooth curve with no scatter. Another 5 expanding spreads and 2 profiles were run, using "a" spacings of up to 600 feet on the expanding spreads and 400 and 500 feet on the profiles. In all cases the electrodes were watered before each reading. The data were very good with little or no scatter.

Summary of Field Observations

The results of these comparative tests indicate the Bison was the easiest and fastest of the three instruments to use. However, it could not handle extremes of resistivity as well as the Geo-Recon. The extremely versatile meters and scale combinations of the Geo-Recon made possible accurate measurement of either very large or very small current and voltage values. The neutralizer circuit in the Geo-Recon is operative at all times, and is routinely used on even the larger scales. This procedure makes it possible to get high accuracy even though the potential electrodes are polarizing.

The BPR instrument was very limited in its range with a high probability of error in its measurements.

DC vs. AC Power Source

A comparison was made between the AC and DC power output as supplied by the three instruments under test. The comparison was to determine what differences existed between the two procedures and the results obtained by each.

The readings from the two DC instruments are given as the voltage and amperage for the direction of current flow. By the nature of the method, a reading is required in each direction. The resistance (R) at each station is then $(E_1+E_2)/(I_1+I_2)$. The amount of time involved in getting the two sets of readings at each station is about equal for the two DC instruments. However, the Geo-Recon has several electronic improvements that make it a more versatile instrument.

The AC instrument requires only one reading at each station. Thus Bison readings take about half as much time as getting Geo-Recon or BPR readings. The Bison also gives its reading as the product of $2\pi R$, which is a feature of the Bison instrument that could be used with either AC or DC, just as either type current could be recorded as E and I. Having the Bison reading as the product of $2\pi R$ simplifies field calculations for surveys using the Wenner array, but complicates them somewhat when the Schlumberger array is used.

Several direct comparisons were made between the three instruments. The results show some differences do exist in the values recorded.

From all indications the main difference in the performance of the Geo-Recon and the Bison has to do with the measurement and output to the ground of E and I rather than the type of current used. The AC provided by the Bison is DC current put through an inverter to create an AC square wave. The excitation frequency is 11 Hz, with an adjustment of ±15%.

The most commonly encountered difficulty when using alternating current is the so-called skin effect (3) problem in which the electric current tends to travel along the surface rather than penetrate to the desired depth of investigation. Probably, current which is being reversed at less than 20 Hz, does not cause skin effect problems, at least not at the relatively shallow depths involved in engineering type investigations. None of the records collected during this investigation revealed any essential depth differences between Bison or Geo-Recon surveys at the same locations.

In order to avoid an electrolysis problem, porous pots are generally used with direct current or very low frequency alternating currents. Both the Bison and the Geo-Recon instruments have balancing circuits for the purpose of neutralizing current from self-potential, telluric, or polarity effects caused by electrical differences between the ground and metal stake. The neutralizer circuits on these two instruments permits an accurate record of resistivity values using metal stakes.

The results of our investigations did not show any significant differences existed in the use or the results obtained by the AC from the Bison and the DC from the Geo-Recon or BPR instruments.

INTERPRETATION

The two basic methods of obtaining resistivity data are profiles and vertical soundings. These two methods yield different data, and require different interpretive techniques. The data from fixed depth profiles were interpreted by contouring subsurface resistivity values and by showing them as profiles. For the vertical electrical soundings, a comparison was made between the curve matching technique and Moore's cumulative method of interpretation.

Interpretation of Fixed-Depth Surveys

Subsurface resistivity contours were drawn from fixed depth profiles run at different locations. These locations were geographically a considerable distance apart and represent a diverse assortment of geologic materials.

The material at 03-ED-49 was a nearly uniform limestone with both open and filled cavities. At the north end of the area of investigation, there is a vertical contact between the limestone and a uniform greenstone. The two rock types each have a uniform level of resistivity so that anomalies can be readily seen and interpreted. The area was reported by Love (5) using interpretations based on profiles which appears to be a satisfactory method of interpreting the data. An interpretation based on the subsurface contours shown in Figures 16 and 17 gave results almost identical to that obtained from the profiles. Using the contours along with the profiles shown in Figures 18, 19 and 20 gives a more complete picture. The contours definitely located the limestone-greenstone contact which crosses the map between Stations 97 and 54 in a vertical direction. The contours also showed the locations and trends of buried sinkholes. This information made possible the location of areas where drilling should be done to get maximum benefit from the boreholes. Locating borehole sites would have been possible, on the basis of the profiles alone, but would have been simpler using both the profiles and contours.

The material at 10-Ama-16 is an interfingered mixture of clays, sands, and fine gravels that contains a number of buried meander streams. There is no uniform background level of resistivity because of the heterogeneous nature of the material. Consequently, the identification of an anomaly is very difficult.

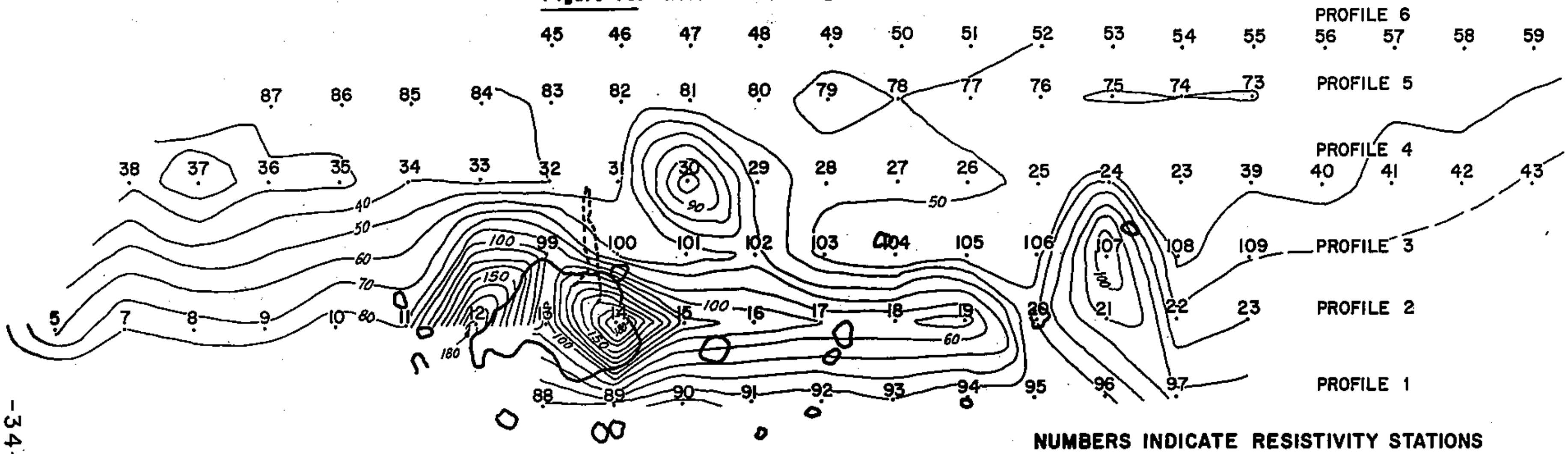
Both profiling and contouring based on the profile data were used in an attempt to locate abandoned mine workings in the area. The profiles and contours for the area along the west roadbed are shown in Figure 21. Neither method proved to be very successful although anomalous conditions were found at four of the five

FIXED DEPTH

WENNER PROFILES, ROAD 03-ED-49, COOL-1965

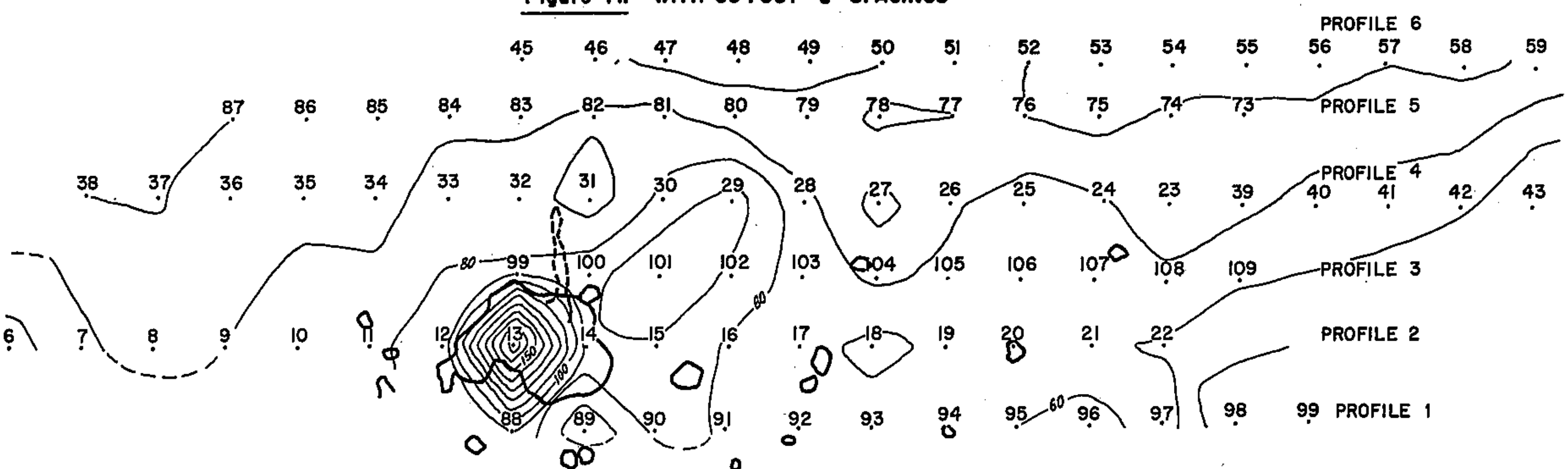
THE PROFILE DATA WERE CONTOURED USING AN INTERVAL OF 10 OHM METERS

Figure 16. WITH 27 FOOT "a" SPACINGS

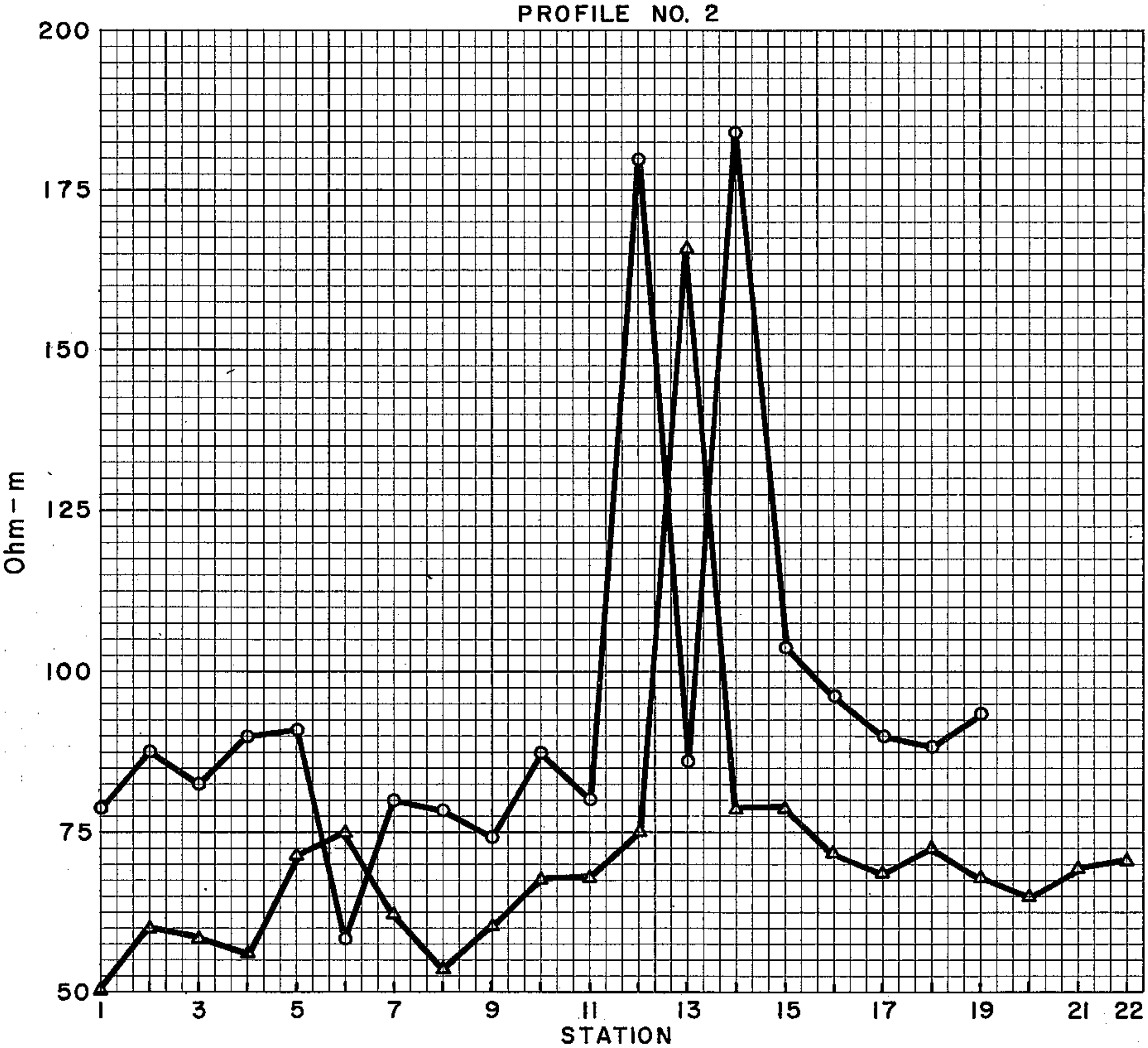


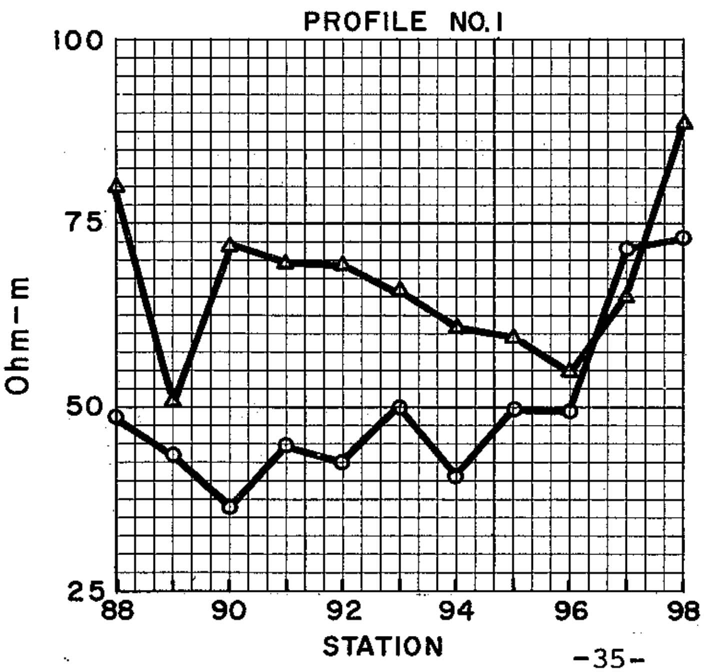
NUMBERS INDICATE RESISTIVITY STATIONS WITH 25 FEET BETWEEN STATIONS.

Figure 17. WITH 50 FOOT "a" SPACINGS



HEAVY SOLID LINES INDICATE CAVITIES AT THE SURFACE.
HEAVY DASHED LINES INDICATE KNOWN CAVITIES AT DEPTH.





Δ - ELECTRODES SPACED 50' APART
O - ELECTRODES SPACED 27' APART

Figure 18. Fixed depth resistivity profiles at Cool.

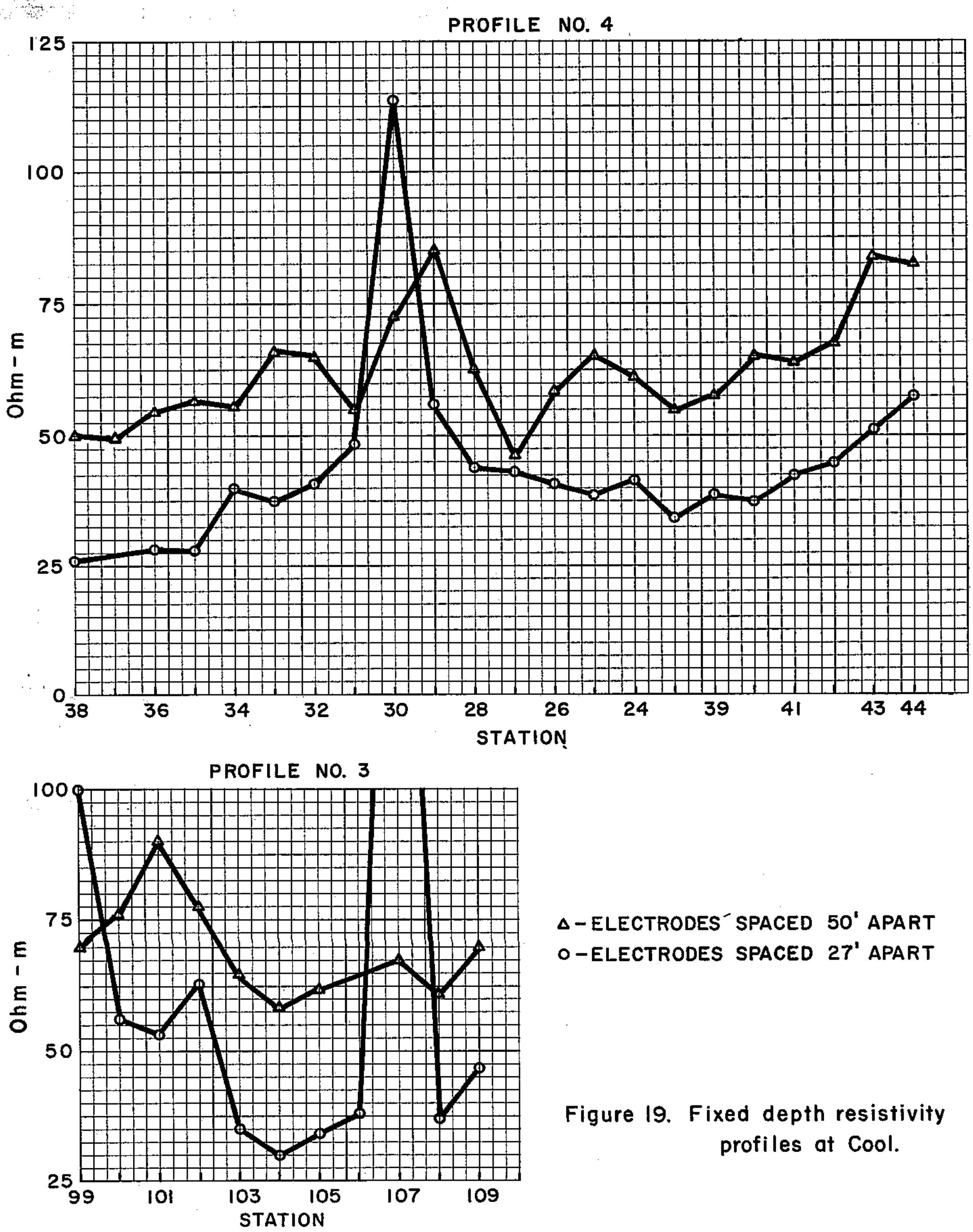


Figure 19. Fixed depth resistivity profiles at Cool.

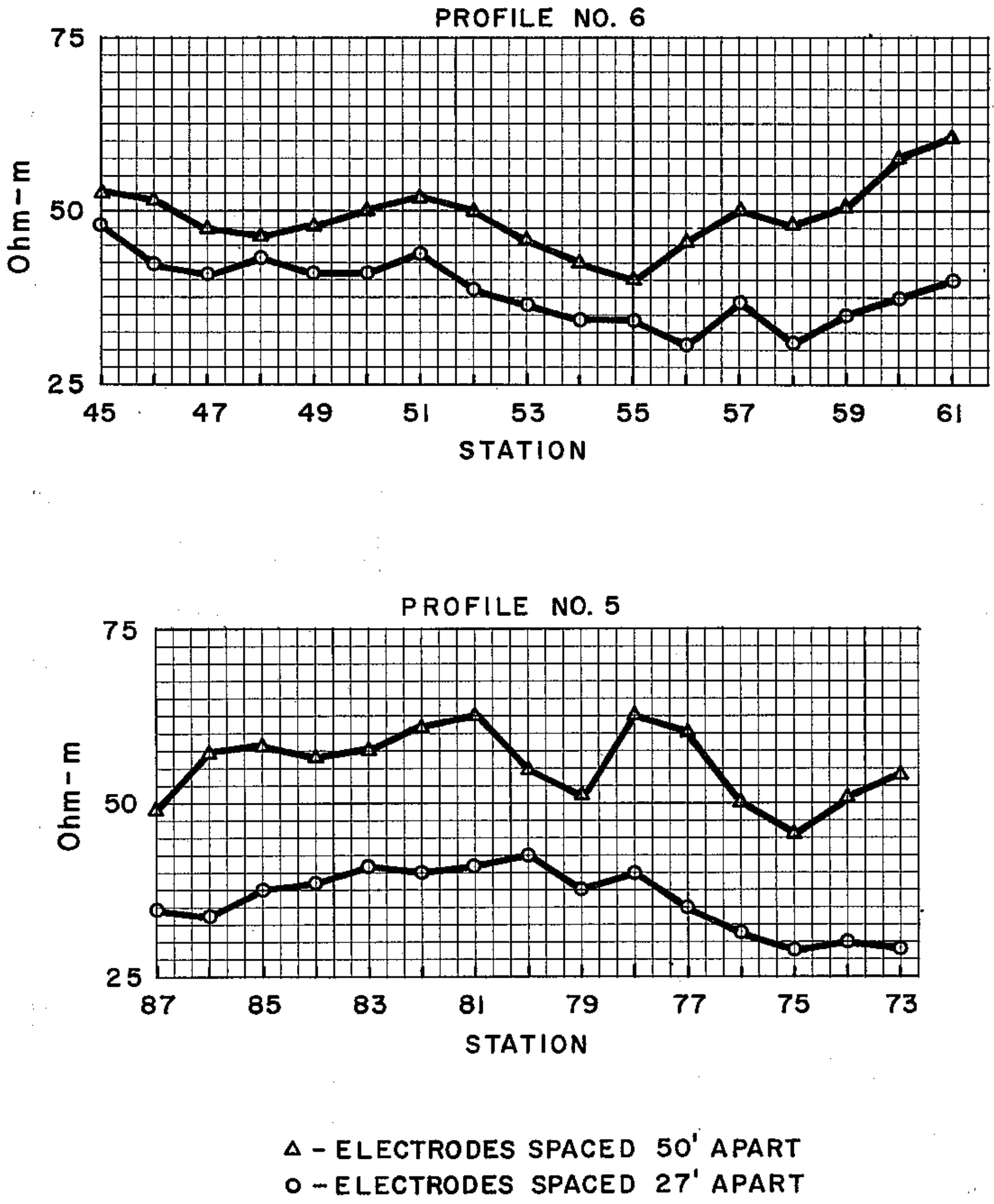


Figure 20. Fixed depth resistivity profiles at Cool.

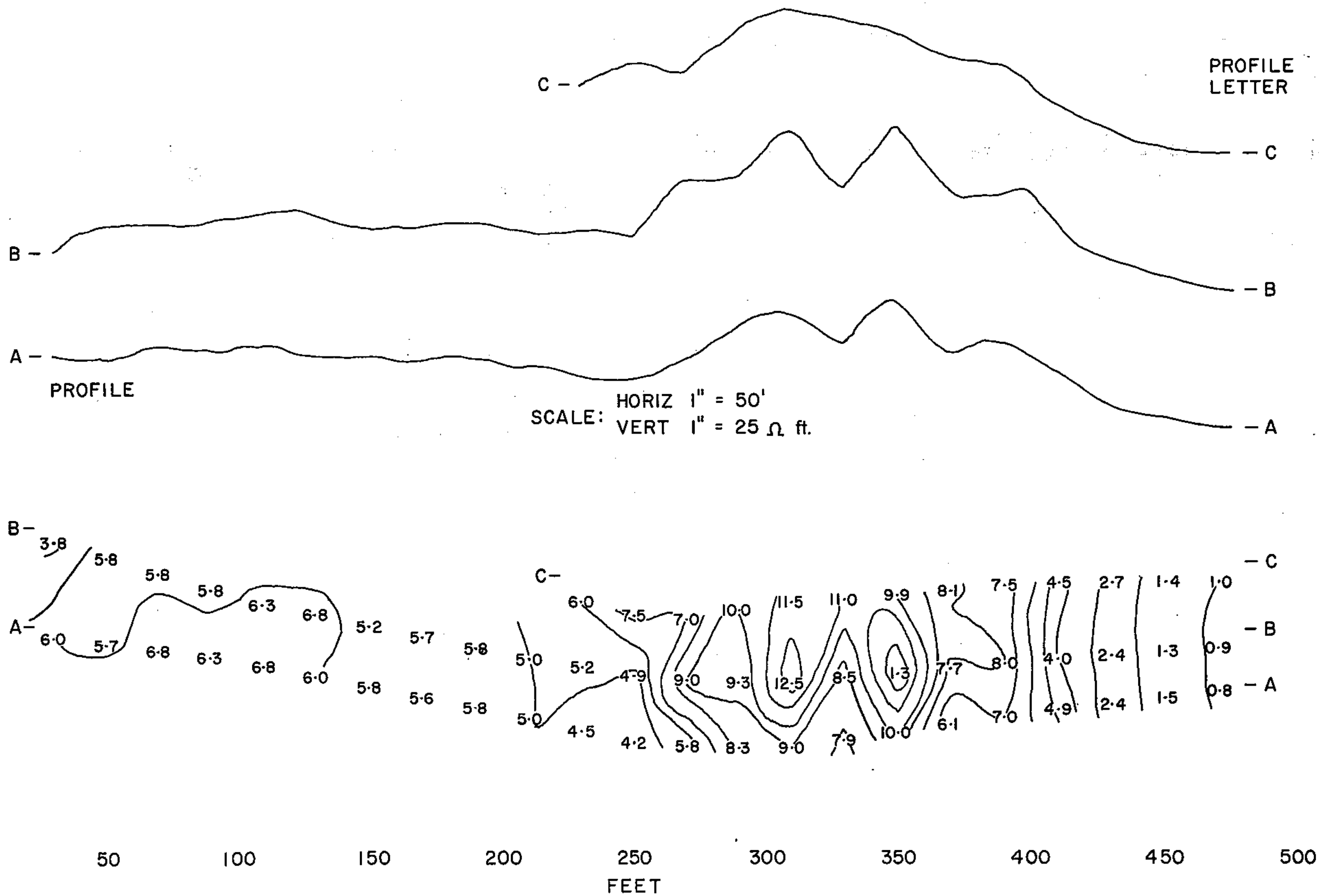


Figure 21. The upper half of the figure shows profiles of Wenner fixed depth surveys along Rd. 10-Ama-16. The lower half is a plan view showing surface locations and the values of the profile readings. Contours were then drawn at intervals of 1 ohm foot.

sites recommended for drilling. At one location a tunnel was located while at three others the material was so soft the six inch auger flight could be pushed.

At 10-Tuo-49,108, the material was geologically complex with different types of sediments intruded by igneous dikes. The main feature of interest was a mine cavity in the limestone that was 80 feet wide by 100 feet long by 55 feet high. The top of this mine is about 50 feet below the ground surface. The mined-out material was a coarsely crystalline white-cream colored limestone. The surrounding rock was a finely crystalline dense dark gray limestone. This material was in contact with a phyllite dipping approximately 80°. Greenstone dikes cut through both the limestone and phyllite.

The background resistivity could not be determined because of the heterogeneous nature of the rock. The limestone phyllite contact is shown plainly by the subsurface resistivity contours as seen in Figures 22-27. Profiles across the area seen in Figure 28 do not show anything that can be interpreted. The conclusion was that the heterogeneous material and complex structure make it impossible to isolate the values that are the result of the mine cavity.

The material at 08-SBd-40 was reasonably consistent meta-igneous rock for which a background resistivity value was obtained. This again was an attempt to locate abandoned mine workings. With the constant background level for the rock, it was possible to identify anomalies along the profile as being cavities.

No contours were drawn of this site due to an insufficient number of readings. It appears, however, that this site could have been successfully contoured, and that the contours would have defined the extent of the workings.

Interpretation of Vertical Electrical Soundings

Data from the vertical electrical soundings were interpreted by the technique of curve matching and by Moore's cumulative method. Previous experience with the cumulative method had often resulted in ambiguous answers. The cumulative method seems to work well for the conditions $\rho_1>\rho_2<\rho_3$. For other conditions, however, it was sometimes impossible to find a solution that agreed with known conditions. A comparison was made of the curve matching and Moore's cumulative method to determine which method was more reliable and consistent with the facts.

The curve matching technique of interpretation is accomplished by matching field curves with theoretical master curves. The field curves are smoothed curves drawn through the apparent

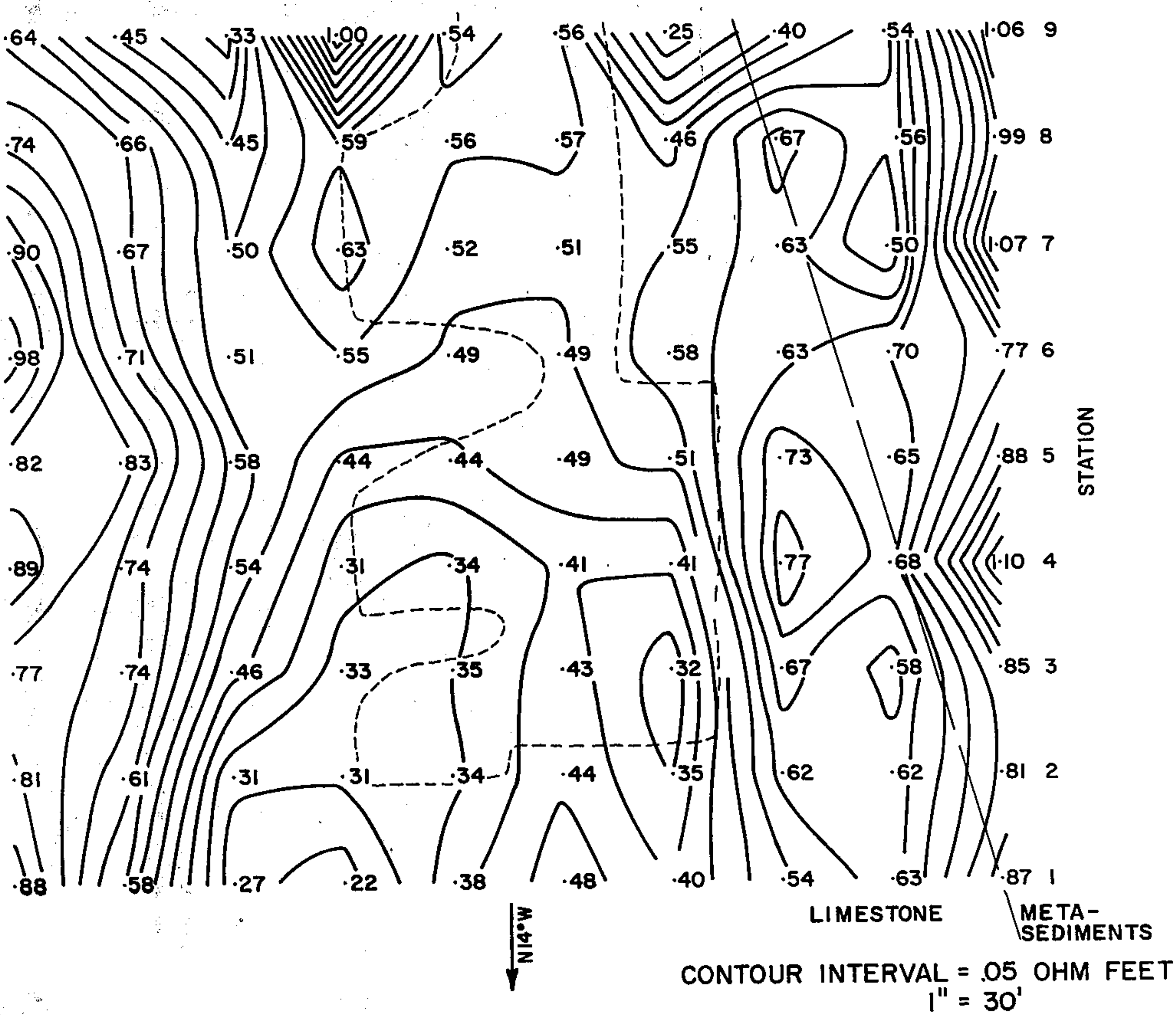


Figure 22. Resistivity contours of a fixed depth gradient survey over the Flintkote mine. The outline of the cavity is shown by short dashes. A geologic contact between limestone and phyllite is shown by long dashes. The distance between potential electrodes was 30 feet.

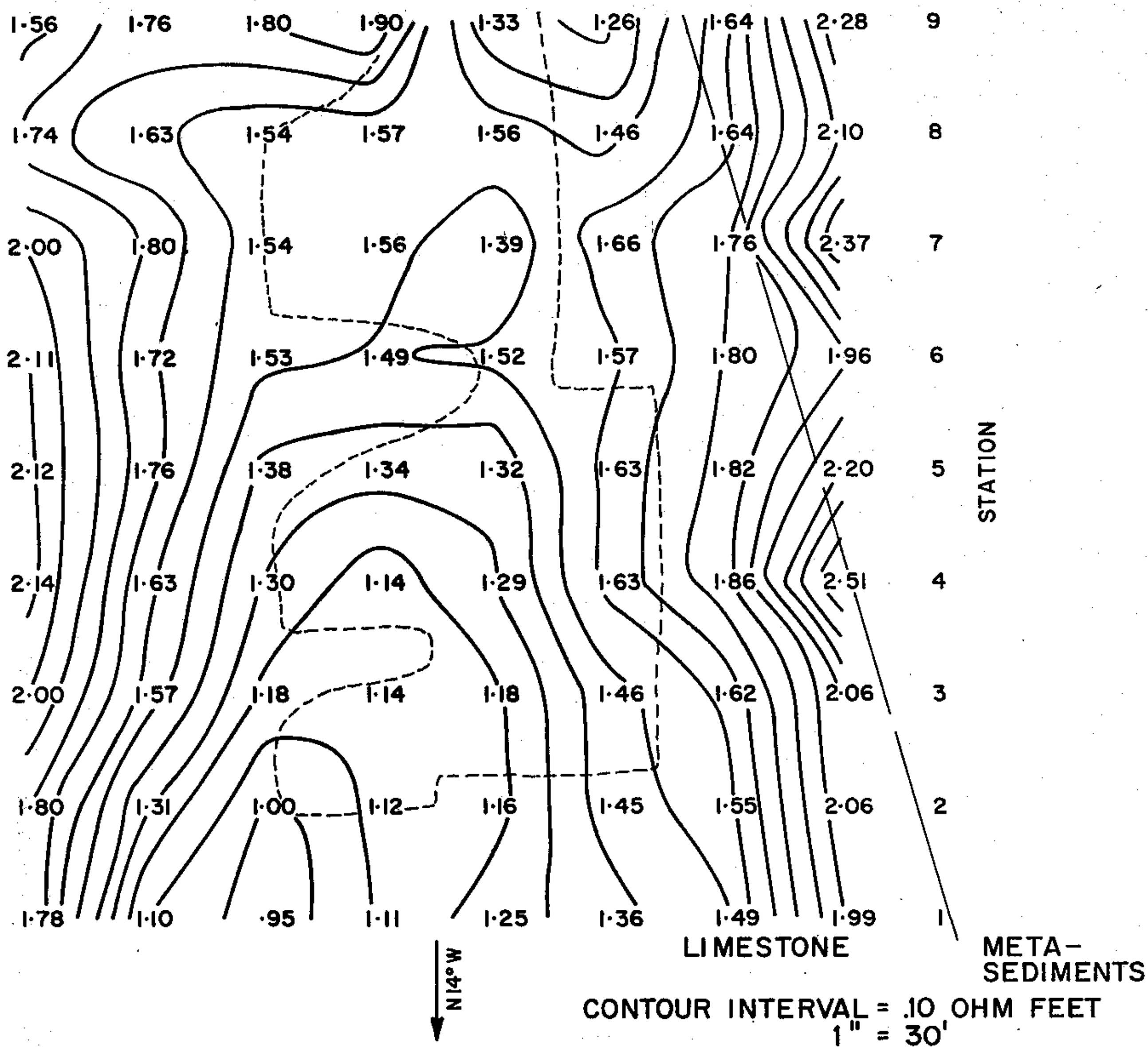


Figure 23. Resistivity contours of a fixed depth gradient survey over the Flintkote mine. The distance between potential electrodes for this survey was 90 feet.

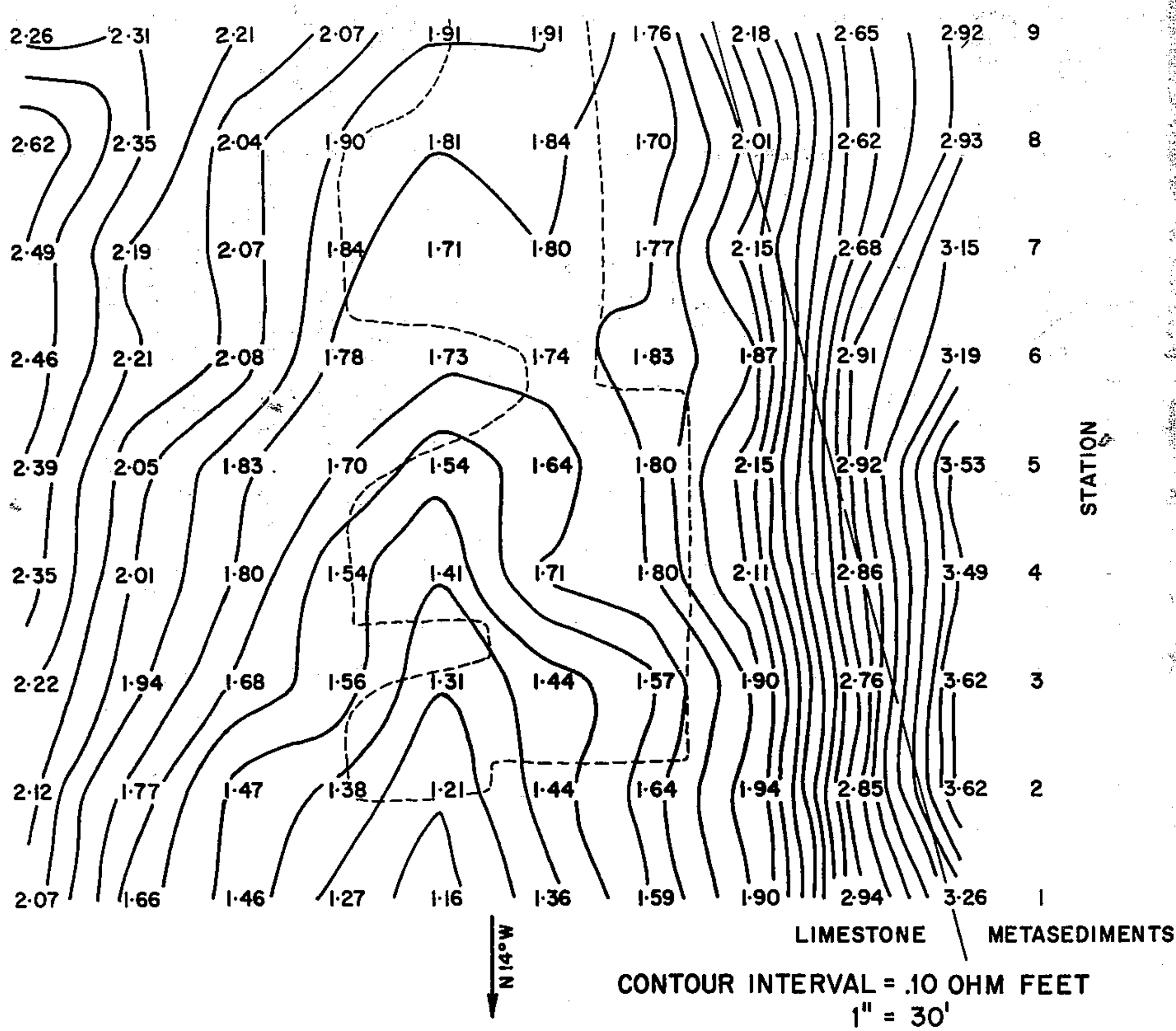


Figure 24 Resistivity contours of a fixed depth gradient survey over the Flintkote mine. The distance between potential electrodes for this survey was 150 feet.

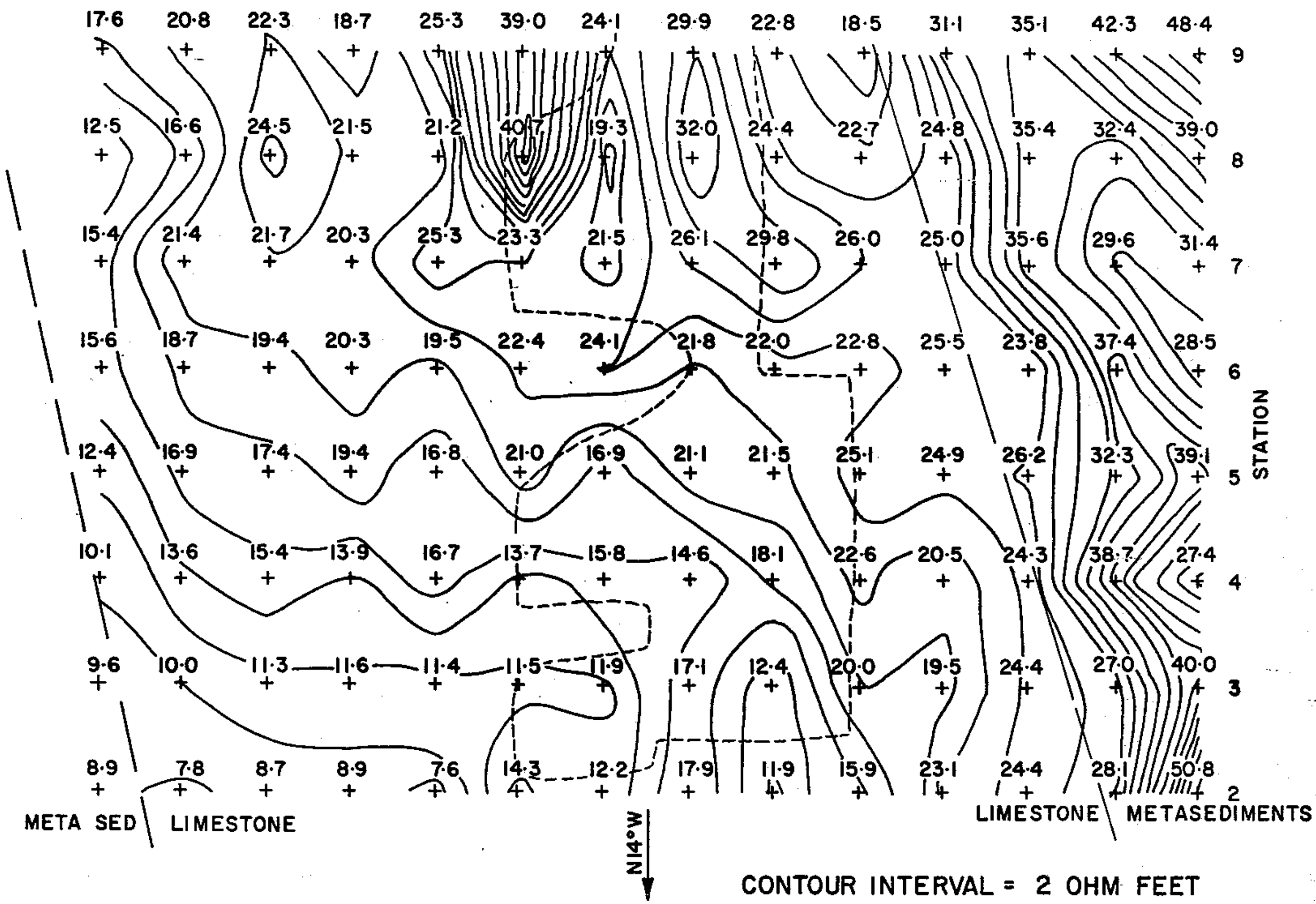


Figure 25. Resistivity contours of a fixed depth Wenner survey over the Flintkote mine. A shallow solution cavity accounts for the local high in the upper left center. The "a" spacing for this survey was 25 feet.

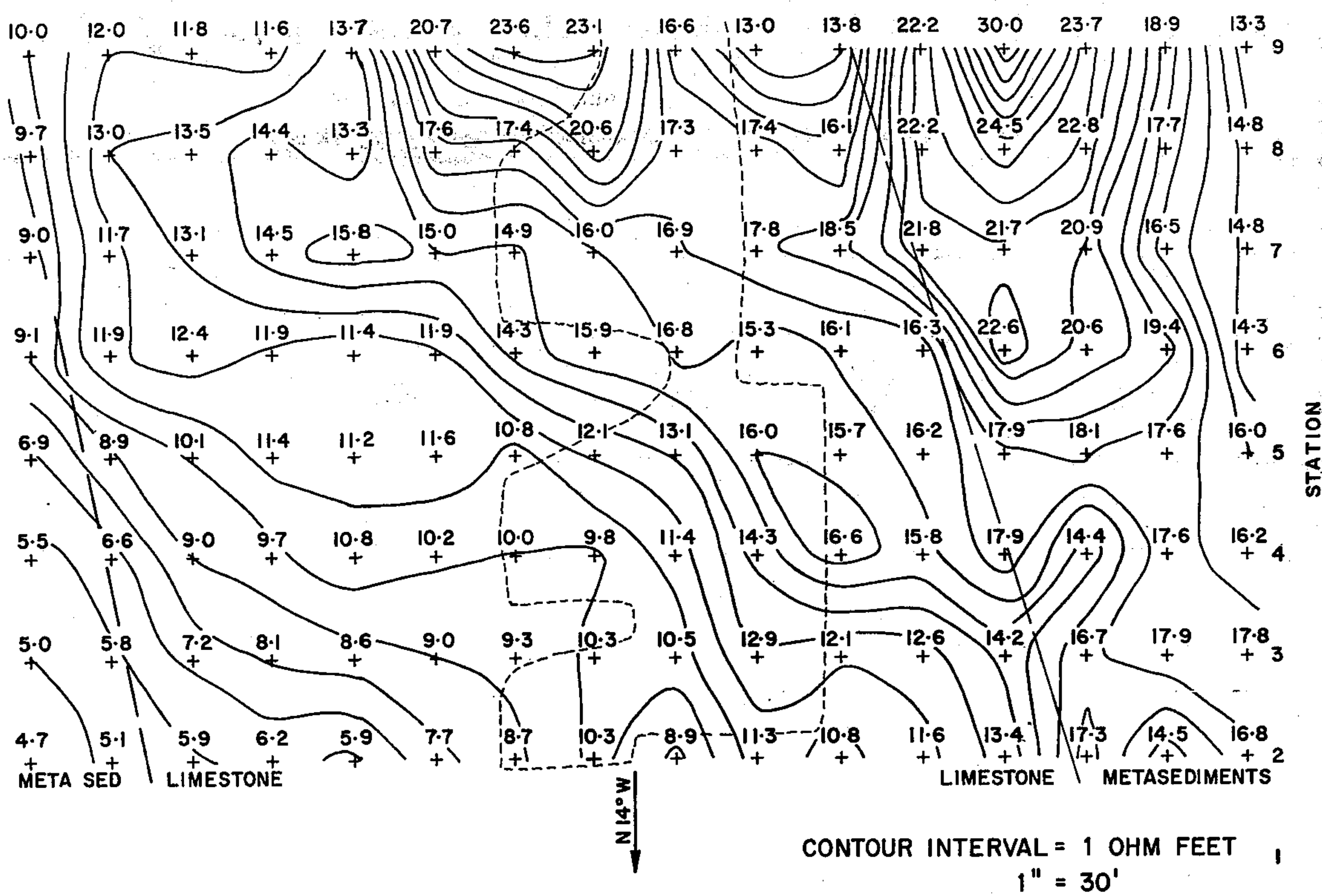


Figure 26. Resistivity contours of a fixed depth Wenner survey over the Flintkote mine, this time using an "a" spacing of 75 feet.

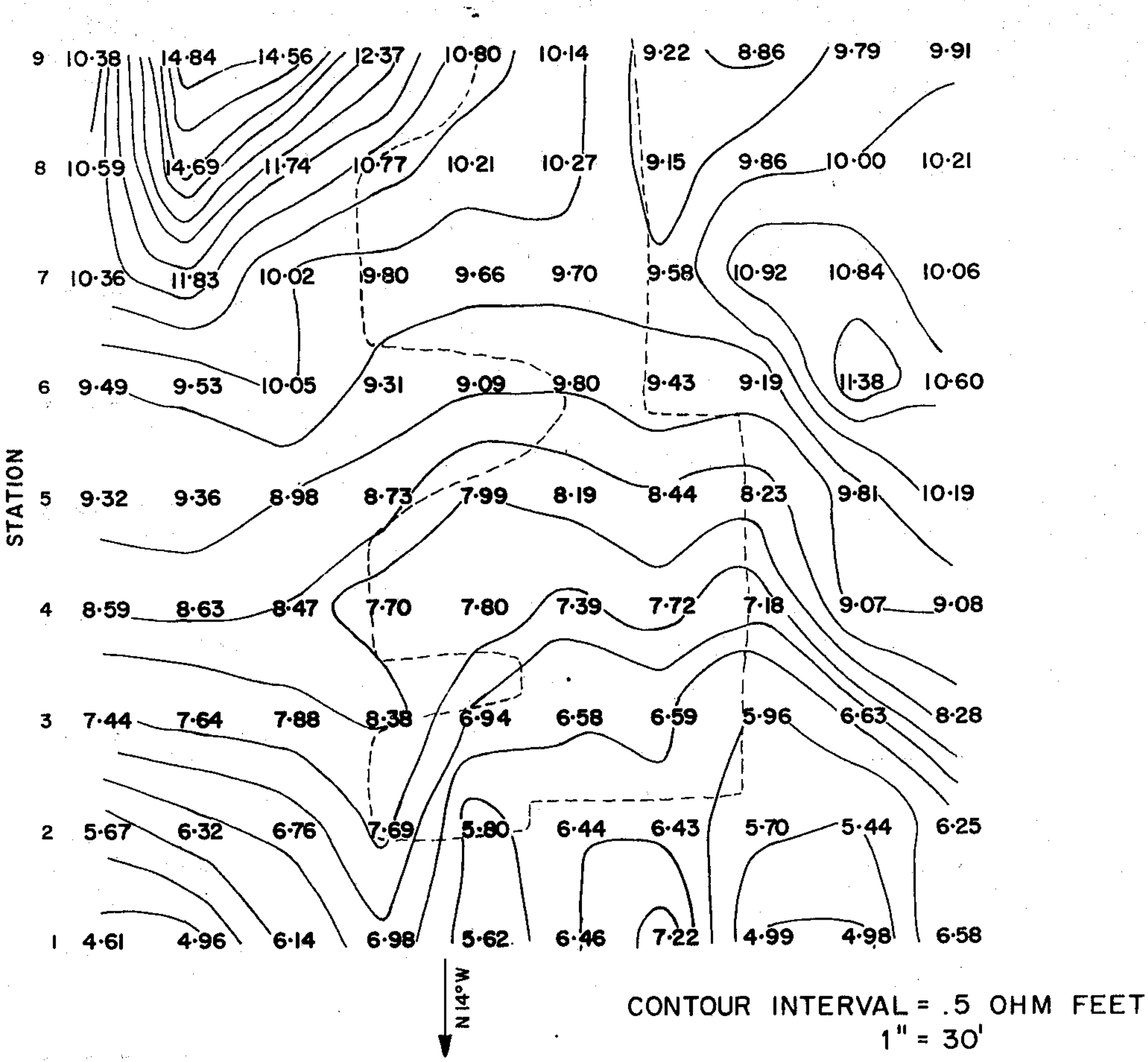


Figure 27. Resistivity contours of a fixed depth Wenner survey over the Flintkote mine using an "a" spacing of 125 feet

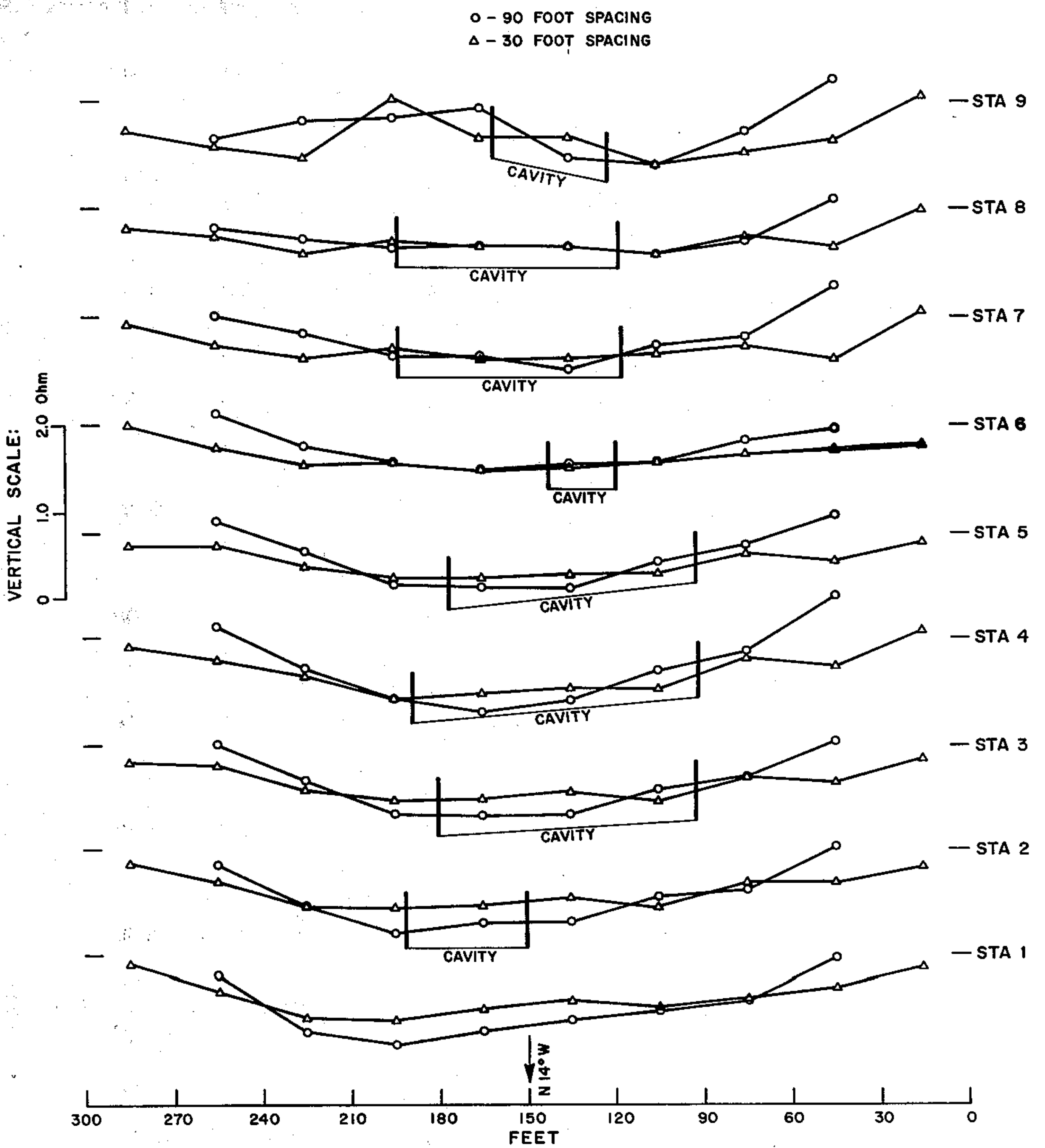


Figure 28. Profile views of the fixed depth surveys contoured in Figures 22 and 23. Two surveys, using different potential separations, are shown crossing the cavity at each survey station. The boundaries of the cavity are shown by the bold vertical lines.

resistivity data points which are plotted as they are collected. A logarithmic expansion of the spread is usually used since the data are plotted on log log paper.

It is not possible to have a curve formed by true readings of vertical changes in the layered media, no matter how abrupt, that cannot be rounded. A curve that cannot be easily rounded signifies that there is a lateral change, a computational error, or possibly an instrument error that accounts for the abrupt change. This is because each additional reading is sampling some amount of additional material, but to do so, the current must also travel through the same section as for the previous reading. Therefore each new reading only modifies the previous reading, and no amount of modification caused by vertical materials changes can cause a new reading that results in an abrupt change in the curve.

The master curves are mathematical calculations of the apparent resistivity curve to be expected for a particular geologic layering condition. The method has a sound foundation in electrical theory and is based on clearly stated mathematical assumptions.

The electrical theory is based on the use of direct current, although alternating current with a frequency of less than 20 Hertz is usually considered acceptable. A comparison of duplicate records obtained at several different locations revealed no significant variations of curve shape between the two instruments tested.

The first comparison of different interpretive methods was made using a theoretical master curve as the data source. The curve was a three layer, type H ($\rho_1 > \rho_2 < \rho_3$) from the Mooney and Wetzel album (7). As chosen, it had depths of 22 and 55 feet, and is shown in Figure 29. Data for the cumulative plot were picked off the curve on the log log paper at even increments and plotted as a linear expansion on 10x10 graph paper. The cumulative interpretation shown in Figure 30 gave depths of 11, 20, 38, 127, 183, 222 and 262 feet.

The next comparison was between the curve matching technique and interpretations published by Moore (9) using the cumulative method. The resistivity lines run by Moore were for the purpose of determining the thickness of concrete pavement and were only long enough for the "a" spacings to approximate the expected depth of investigation. There was good correlation between the thickness of the concrete and the values as determined by Moore. His method also gave other answers that he interpreted as being the depth to reinforcing steel, depth of penetration of curing compound and other unknown qualities.

NO X64 (MOONEY & WETZEL)

RESISTIVITY RATIO = $1 : \frac{1}{10} : 1$

DEPTH RATIO = 2 – 5

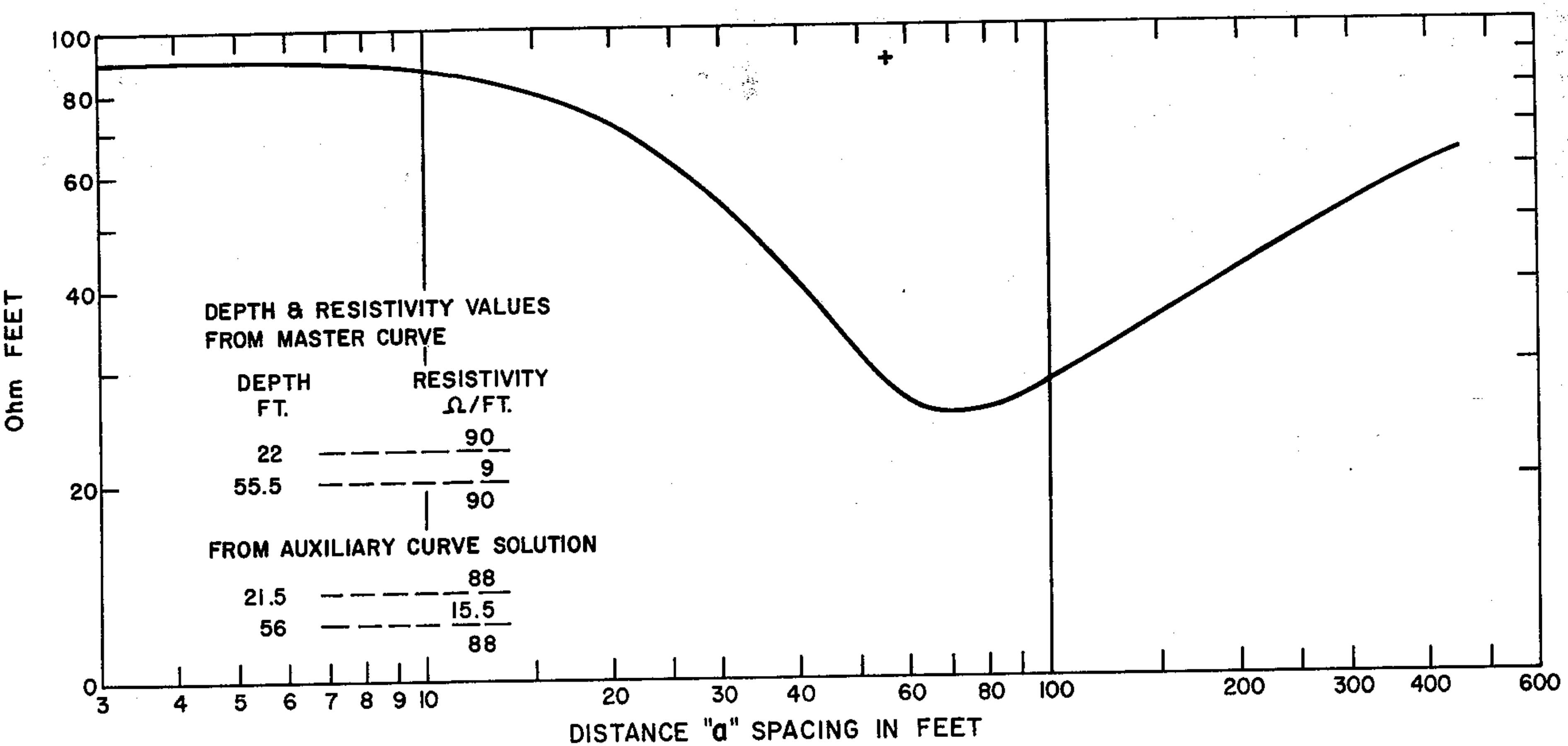


Figure 29. Type H master curve from the album by Mooney and Wetzel. The position of the curve was arbitrarily chosen to give the indicated depth and resistivity values.

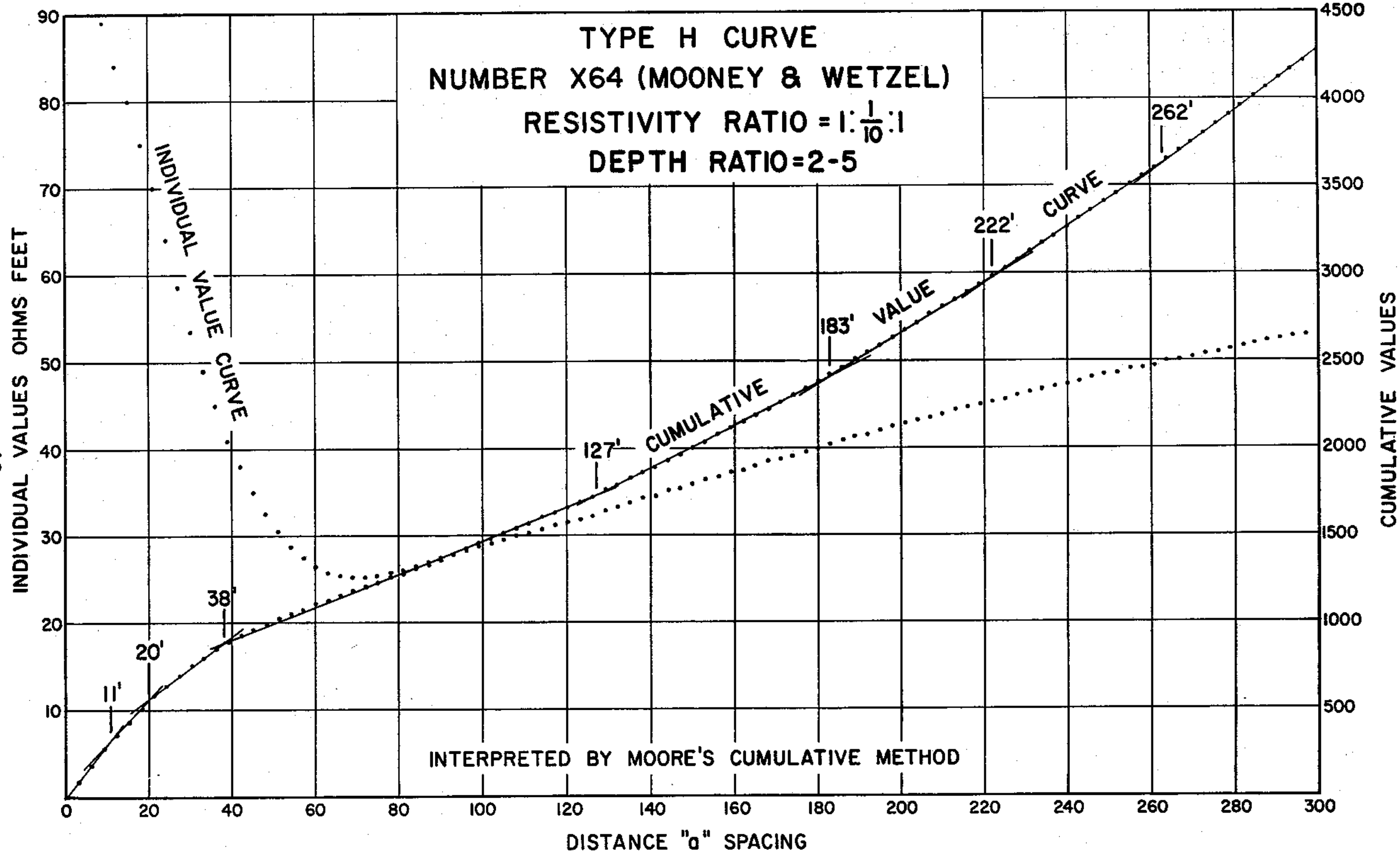


Figure 30. The cumulative solution of the curve shown on Figure 29.

The data were replotted on log log paper and interpreted by the curve matching technique. Some difficulty was experienced in interpreting the lines, which due to their short length, did not define the full shape of the curves. Interpretations were made of three of the curves and then verified by a computer program which drew master curves for each of the interpretations. Table 1 shows the depths from both methods, including the resistivity value for each layer by the curve matching technique, and the nominal depths expected to be found at each location.

The published interpretation of Figure 1 is reproduced in Figure 31, and shows only one depth although the cumulative and individual value curves both show a definite change at 3.4 feet. Figure 32 shows the data replotted on log log paper and interpreted by curve matching. The curve matching solution considers this line a very clear three layer case. The computer curve, drawn using the interpretation of Figure 32 is shown in Figure 33.

Moore's Figure 2 is shown reproduced in Figure 34. The data were replotted on log log paper and interpreted as shown in Figure 35. The curve matching method gives a clear four layer case, and again agrees with the cumulative method on the thickness of the concrete. Moore states that the intermediate depths of 4.4 and 6.56 were discounted as not being significant, based on the absence of recognizable trends in the individual value curve. The author considers the graph to have recognizable trends for both of these depths. The computer curve based on the in terpretations shown in Figure 35 is shown in Figure 36.

Moore's Figure 3 is reproduced in Figure 37. The data was replotted on log log paper and interpreted as shown in Figure 38. Both the cumulative method and the curve matching method give three depths, although not the same three. Both methods agree on the total depth of slab and the underlying sand and gravel base, but not on the other depths. The nominal depth of concrete was 5 inches, and was located by the cumulative method at 5.35 inches. However, the author cannot recognize any trend on the individual value curve at this depth. The computer curve based on the interpretation of Figure 38 is shown in Figure 39.

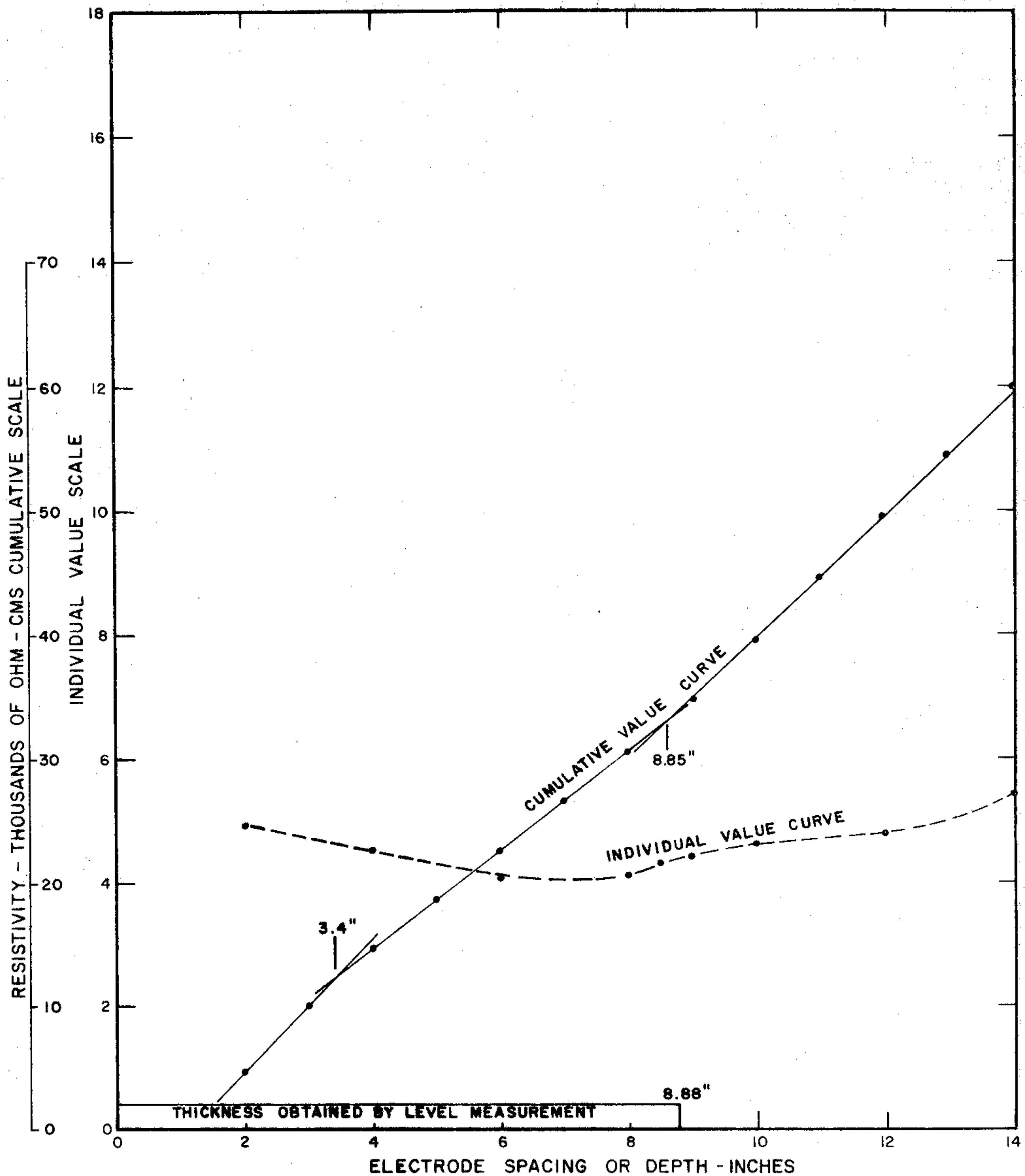


Figure 31. A REPRODUCTION OF CURVES FROM MOORE'S FIGURE 1, p. 50, SHOWING HIS INTERPRETATION OF A SINGLE DEPTH OF 8.85". AN ADDITIONAL DEPTH OF 3.4" HAS BEEN INTERPRETED BY THIS AUTHOR.

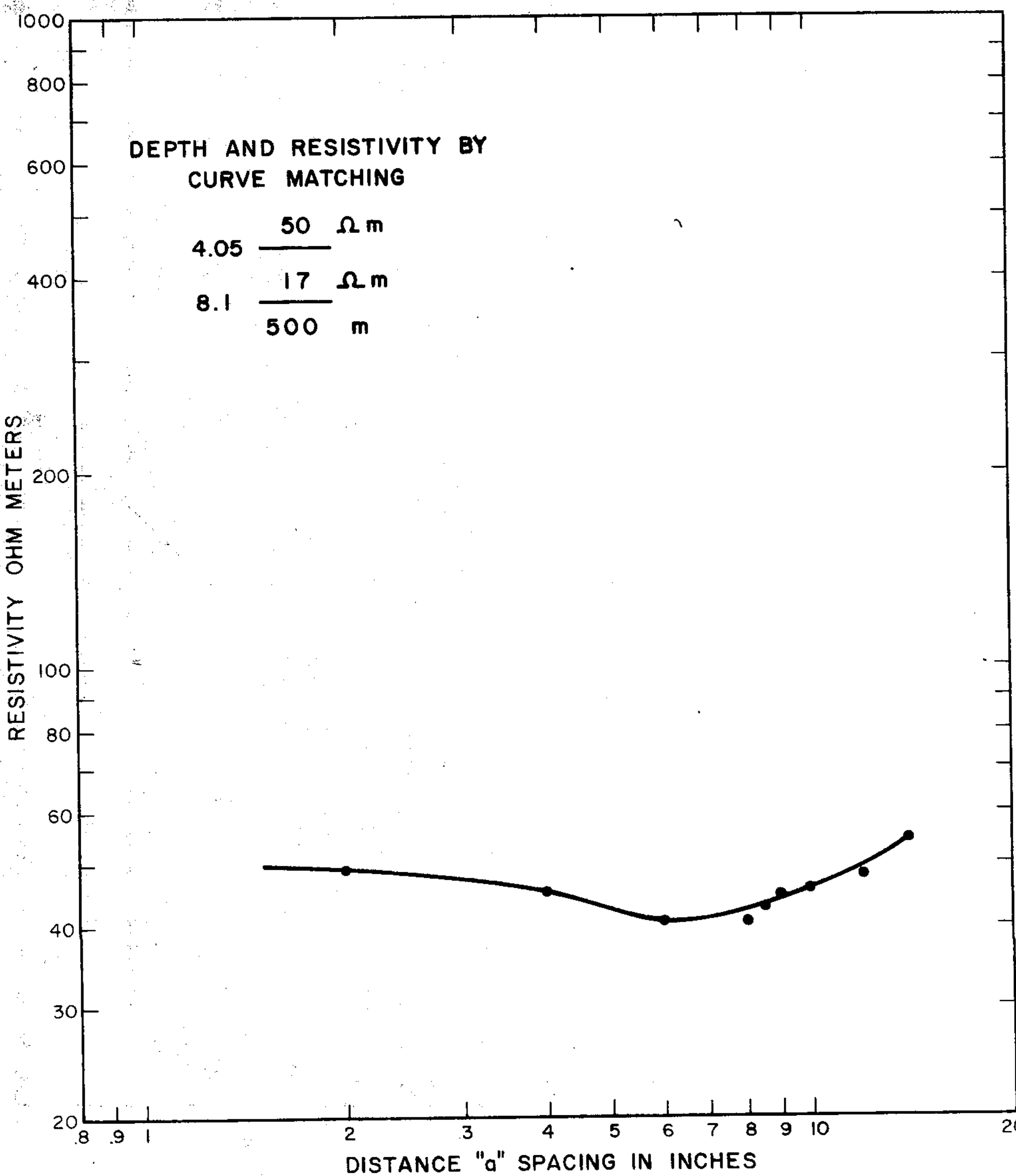


Figure 32. MOORE'S FIGURE 1 REPLOTTED ON LOG LOG PAPER, SHOWING THE PRELIMINARY INTERPRETATION BY CURVE MATCHING.

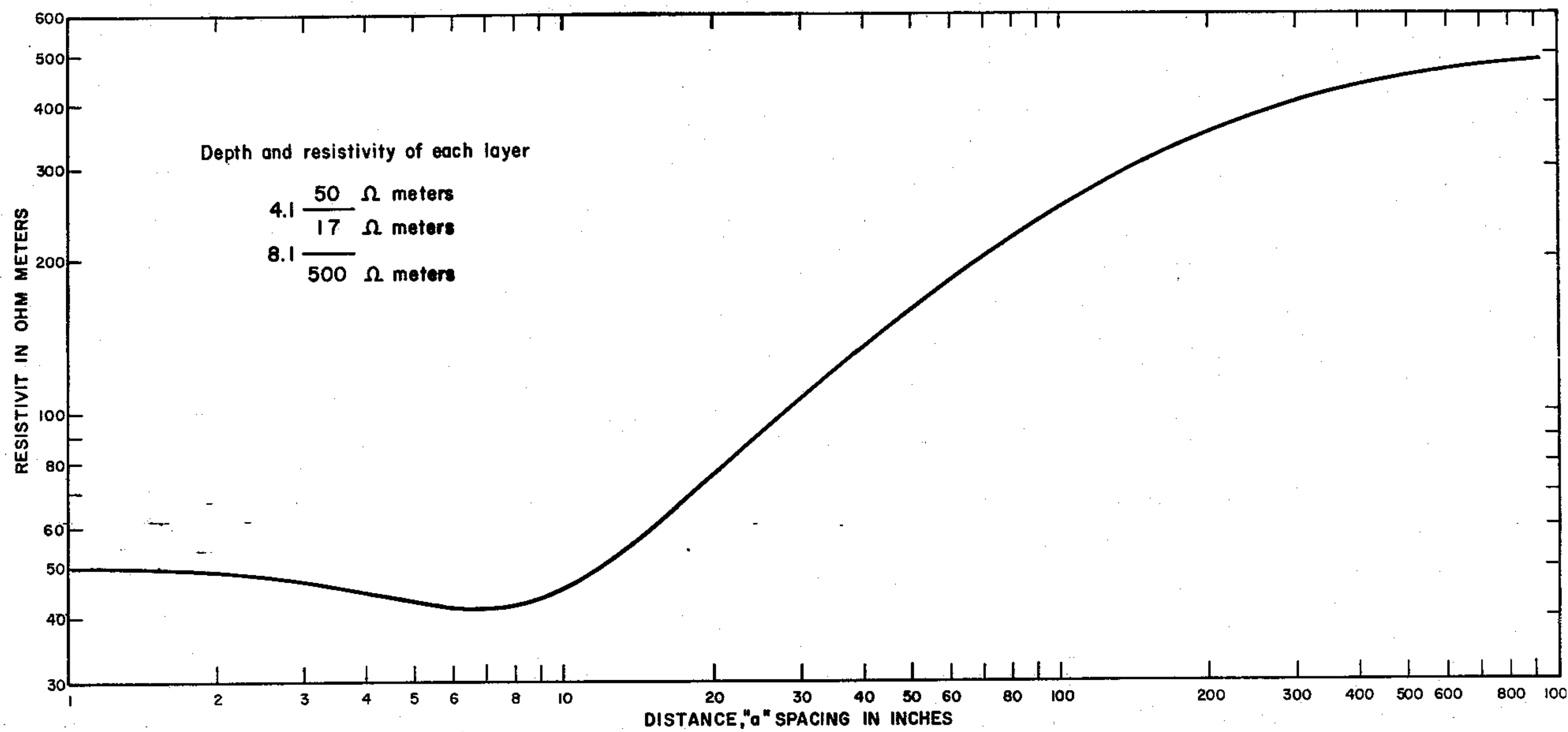


Figure 33. Computer curve of the interpretation of Figure 31 made by curve matching techniques.

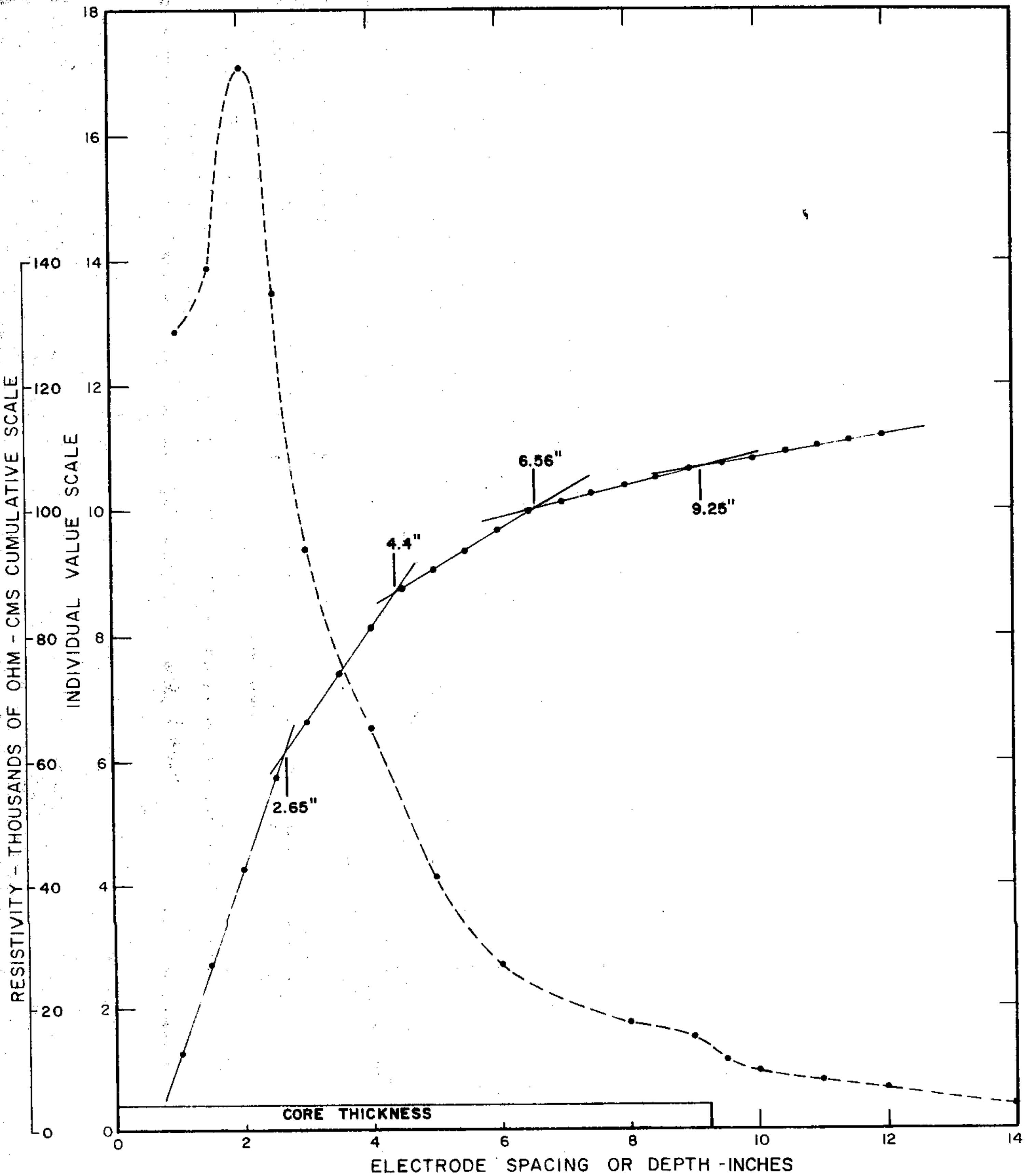


Figure 34. A REPRODUCTION OF CURVES FROM MOORE'S FIGURE 2, p. 51, SHOWING HIS INTERPRETATIONS OF DEPTHS OF 2.65" & 9.25" ADDITIONAL DEPTHS OF 4.4" & 6.56" WERE INTEPRETED BY THIS AUTHOR

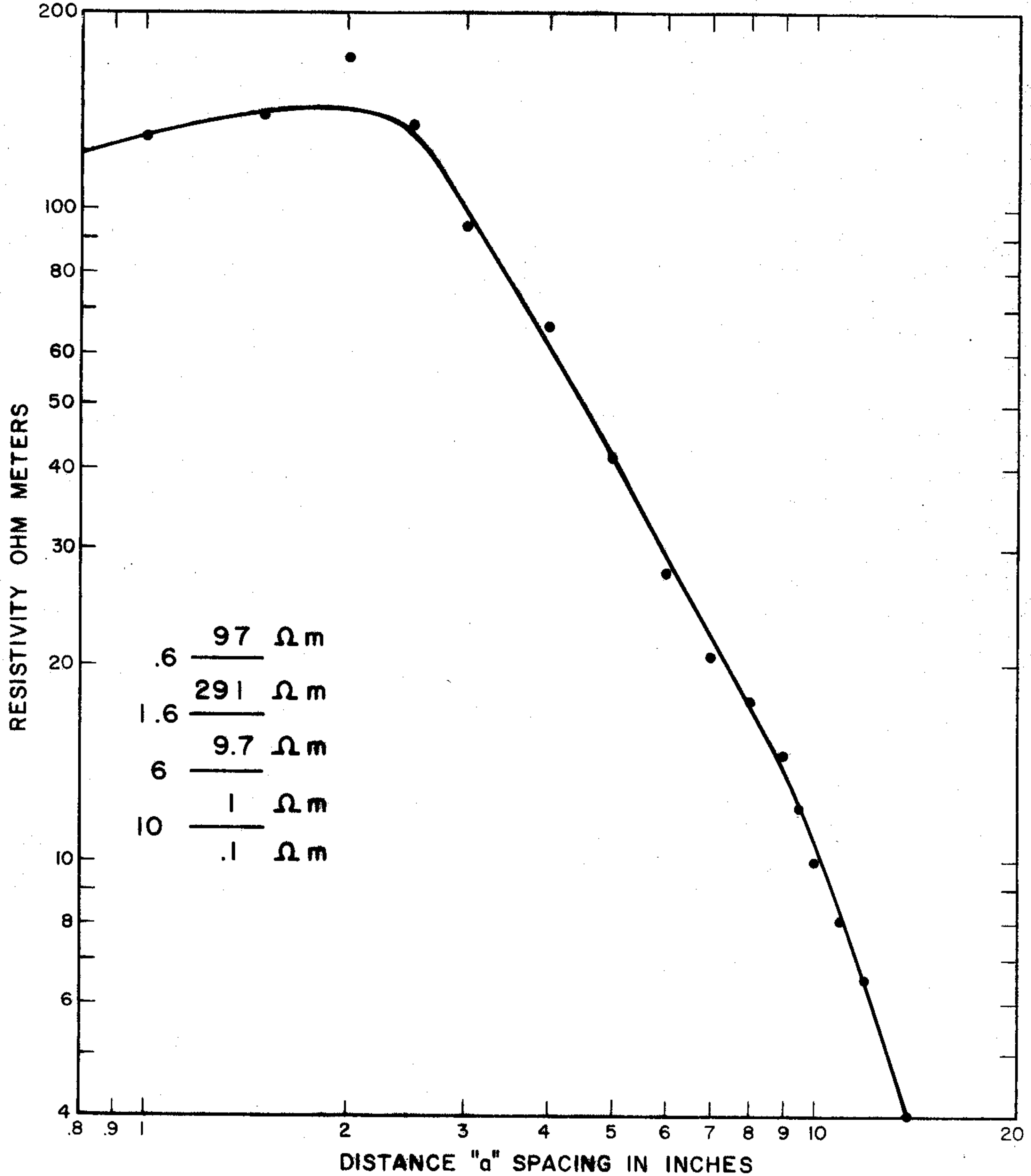


Figure 35. MOORE'S FIGURE 2 REPLOTTED ON LOG LOG PAPER. A PRELIMINARY CURVE MATCHING INTERPRETATION IS SHOWN.

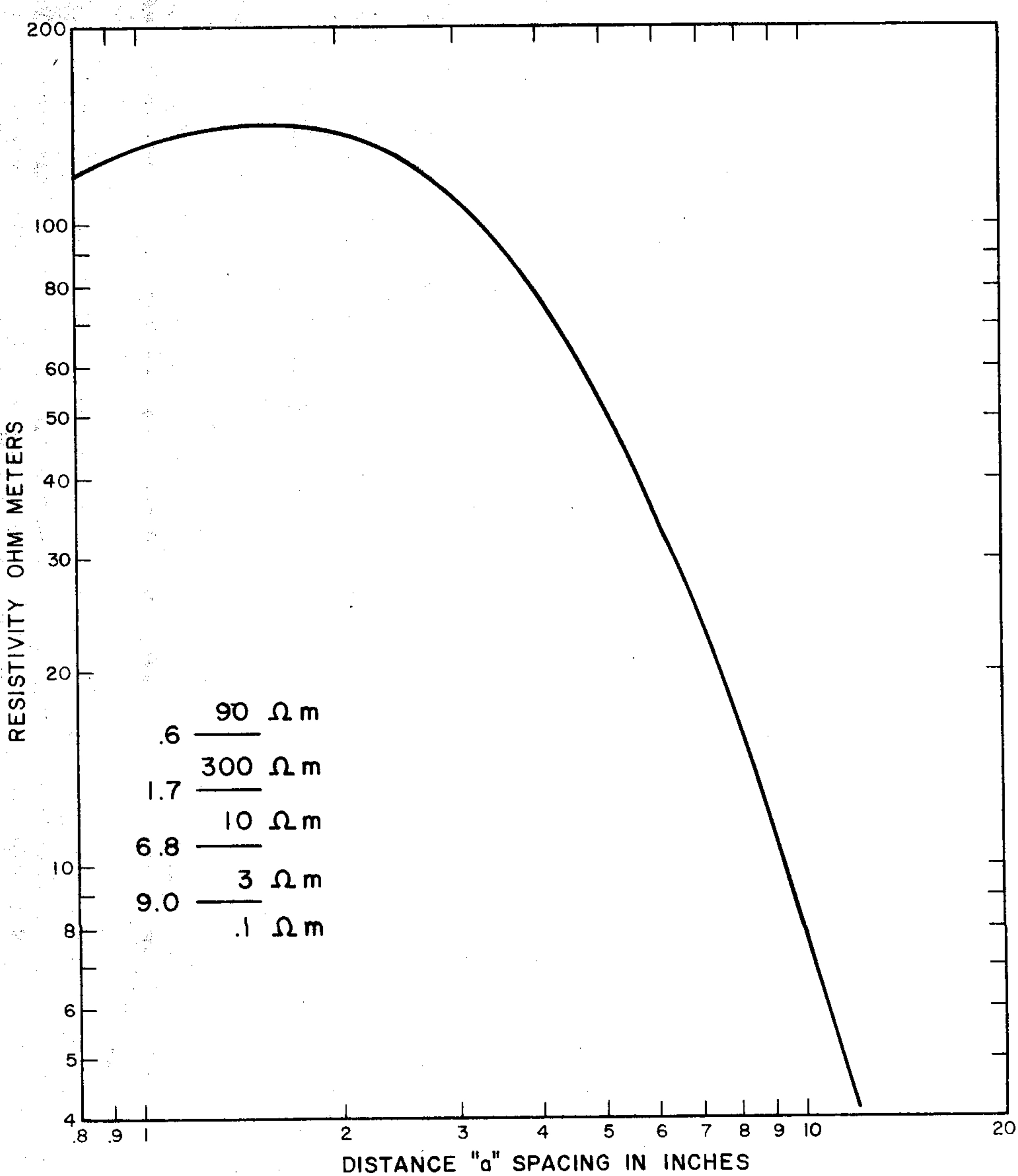


Figure 36. COMPUTER CURVE OF THE INTERPRETATION OF FIGURE 35 MADE BY THE CURVE MATCHING TECHNIQUE. DEPTHS AND RESISTIVITIES ARE SHOWN.

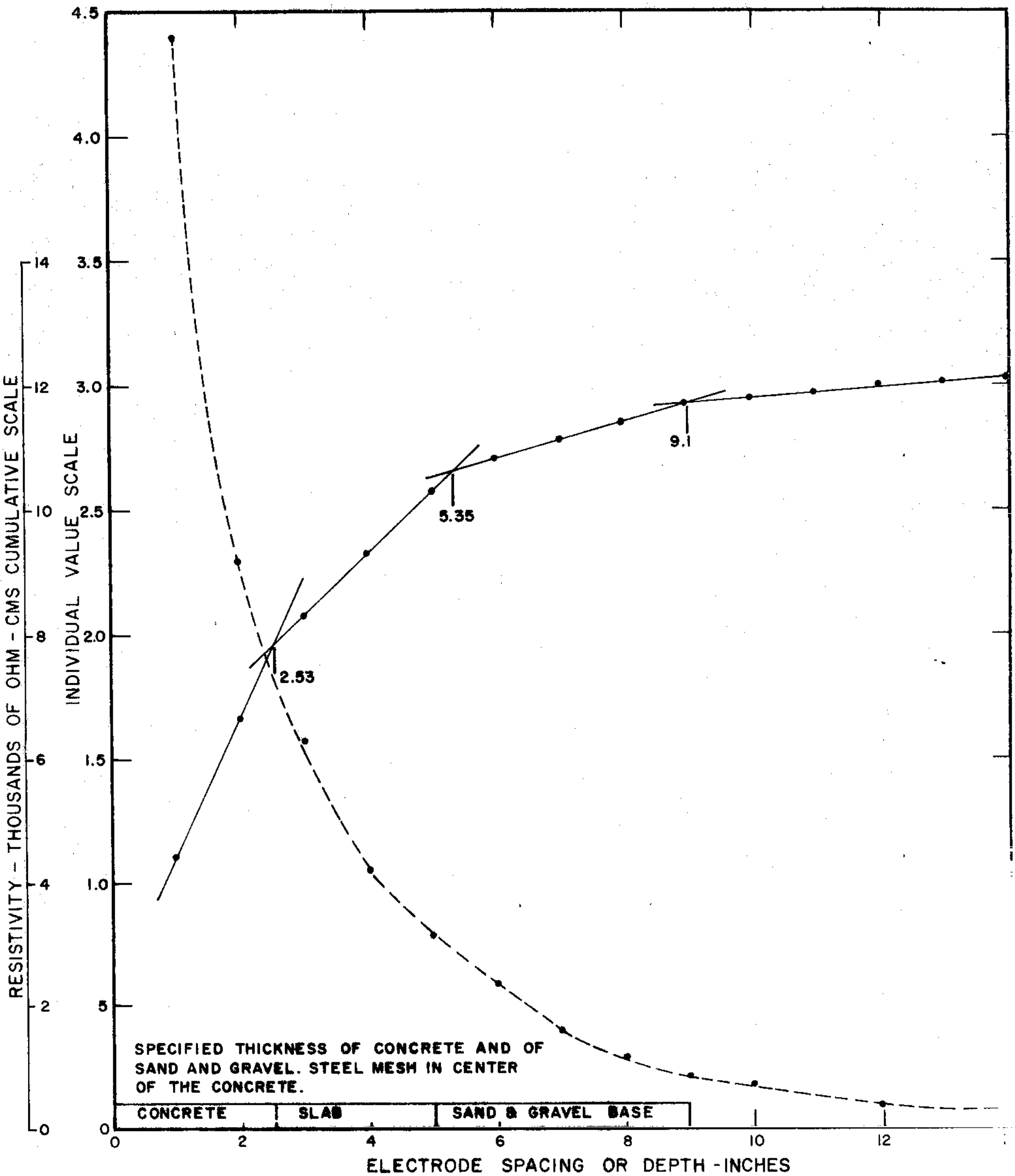


Figure 37. A REPRODUCTION OF CURVES FROM MOORE'S FIGURE 3, p. 51, SHOWING HIS INTERPRETATIONS OF DEPTHS OF 2.35", 5.35" AND 9.1 INCHES.

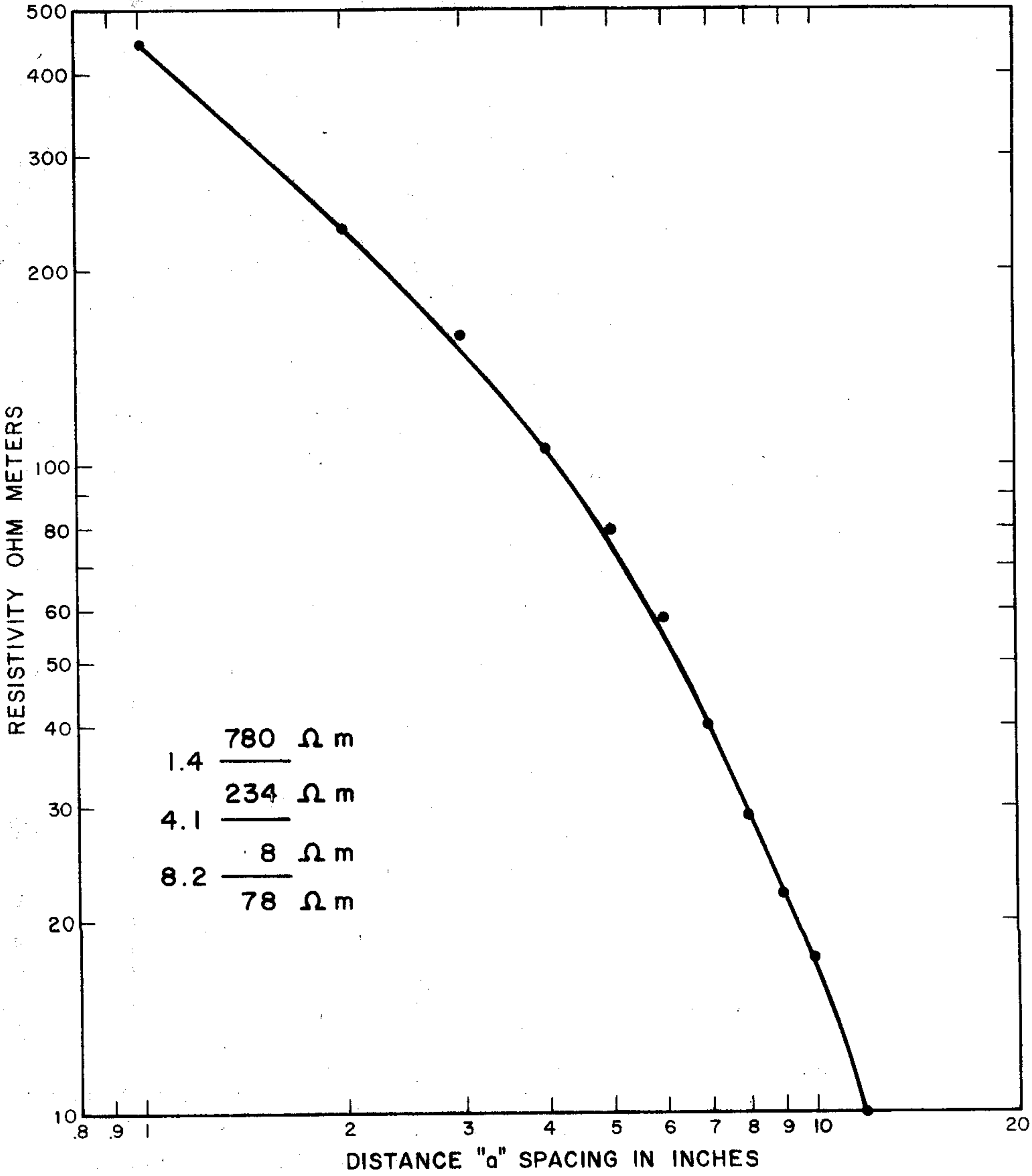


Figure 38. MOORE'S FIGURE 3 REPLOTTED ON LOG LOG PAPER. THE PRELIMINARY INTERPRETATION IS ALSO SHOWN.

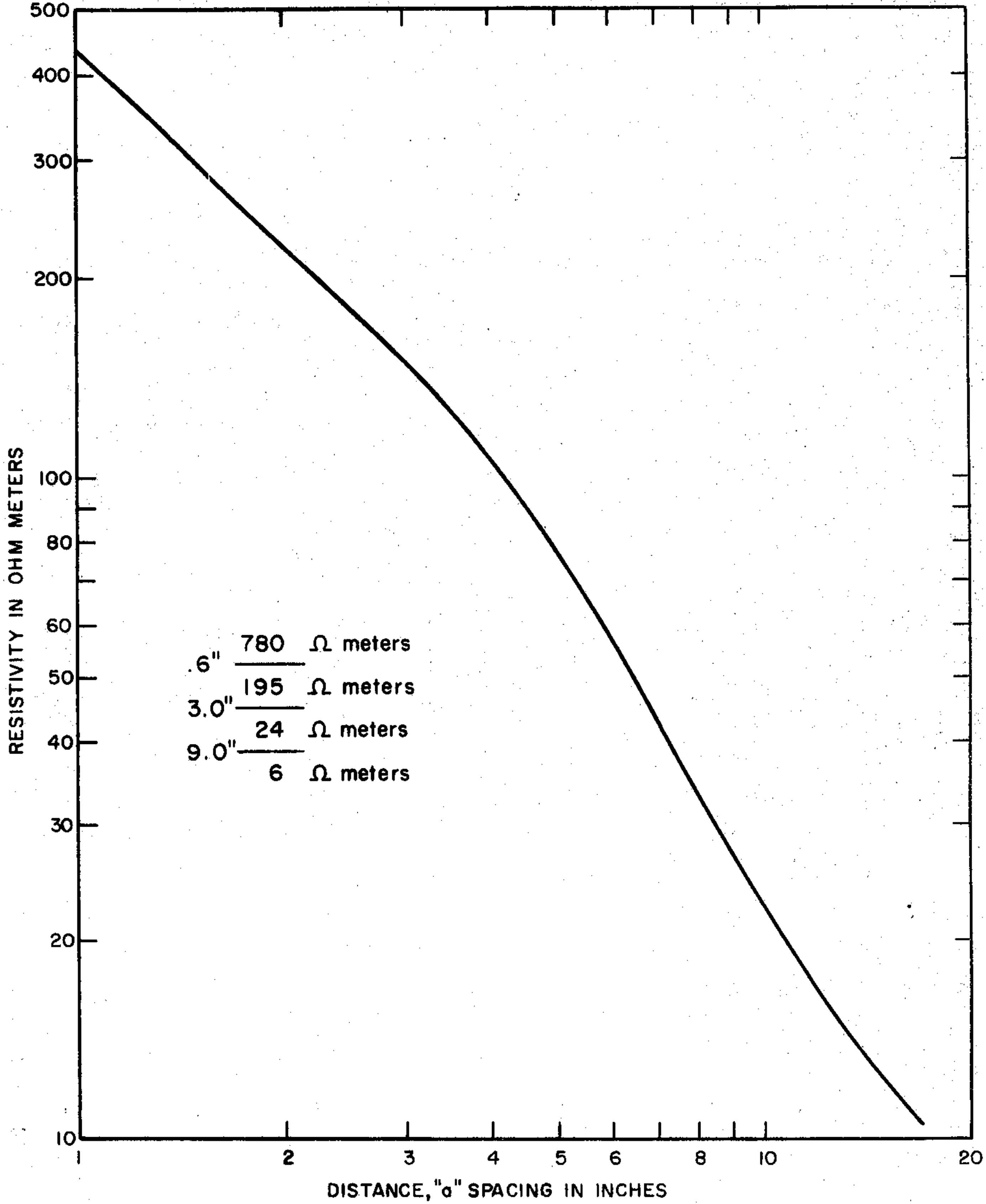


Figure 39. Computer curve of the interpretation of Figure 38 made by the curve matching technique.

Table 1

A comparison of results obtained by the cumulative method with those obtained by curve matching. Data from Moore's paper.

Line No.	Depths by Cumulative Method	Depths by Curve Matching	Nominal Depths Expected	Resistivity of layers (from curve matching)
1	3.4*			50
	8.85	4.1	8.88	17
		8.1		500
2	2.65	.6	2.65	90
	4.4*	1.7		300
	6.56*	6.8	9.27	10
	9	9		3
				.1
3	2.53	.6	2.4±	780
	5.35	3	5±	195
	9.1	9	9	24
				6

Cumulative depths marked by an asterisk are depths shown by intersecting straight line segments of the cumulative curve, that were considered by Moore as not being significant. Additional depths of approximately .6 are indicated by the individual value and cumulative value curves for lines 2 and 3.

On lines 2 and 3, the curve matching technique shows a first depth of 0.6 inches. An examination of the individual value curve of these two lines indicates they must have a very thin first layer where the curve becomes asymptotic, but which is too thin to be detected by the cumulative method. There are intermediate depths indicated by the cumulative curve of line 2, which are considered insignificant by Moore, but appear significant to the author. In contract, line 3 has a depth considered insignificant by the author, but significant by Moore. Based on these interpretations, advance knowledge of local conditions would have been necessary to determine which depths were the ones desired.

A third comparison was made of data from a field curve collected using a logarithmic expansion of the spread as shown in Figure 40. The curve was first interpreted by curve matching techniques. Data points were picked from the log log graph on a linear basis and replotted as a linear expansion on a 10x10 graph. The data were then interpreted by the cumulative and by the Narayan and Ramanujachary inverse slope method. The depths as determined by each of the three methods are shown in Table 2, along with resistivity values of each layer for the curve matching and Narayan and Ramanujachary methods. The three different methods of interpretation are shown in Figures 41, 42 and 43.

Data from another line, which was also expanded logarithmically, were then interpreted in a like manner by the curve matching and the cumulative methods. The field curve of line 1 at Sonora is shown in Figure 44, along with the interpretation made by auxiliary curve matching. This interpretation gave depths of 11.5, 24, 48 and 125 feet. Figure 45 is a computer curve which matched the field curve using depths of 12, 24, 48 and 124 feet. The cumulative method, shown in Figure 46, gave depths of 15, 25, 43, 76 and 170 feet. Seismic depths showed soil to 9 feet, broken rock to 25 feet and then hard rock. A known cavity was under the line with the roof at a depth of 50 feet and the floor at a depth of 105 feet.

Data for use with the cumulative method must be collected using a linear expansion of even increments. The data are usually plotted on 10x10 graph paper as collected in order to assure the validity of the readings. A minor amount of scatter and sharp inflections of the line are usually tolerated and have no apparent deleterious effect. There is even evidence to indicate the scatter and occasional sharp inflection points are what makes the method work.

The same data, as used for the cumulative method, if replotted on log log paper often has such scatter that it cannot be interpreted by curve matching techniques. A point that appears slightly off

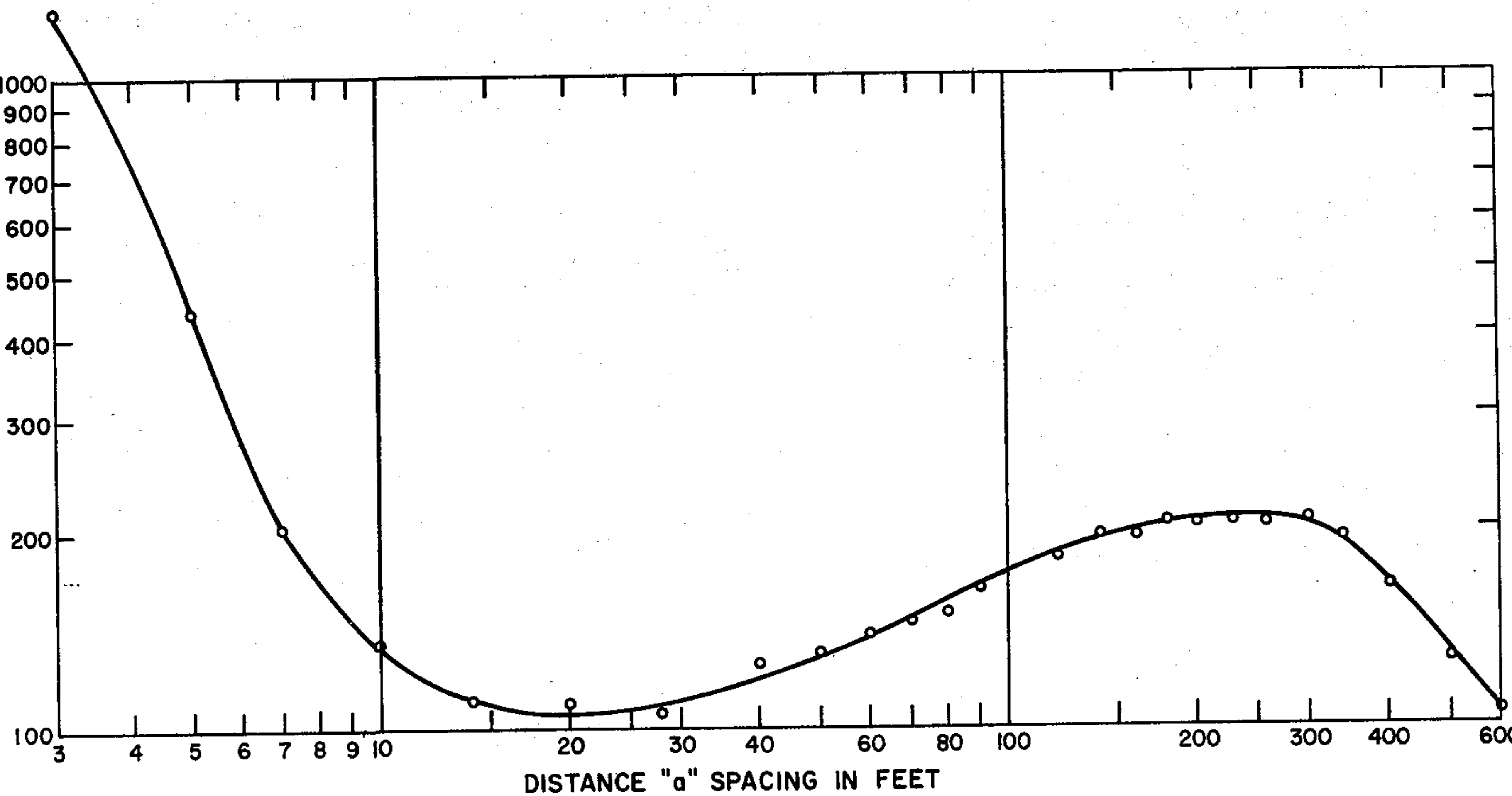


Figure 40 Field curve of Line 3 at Midway Rest Stop

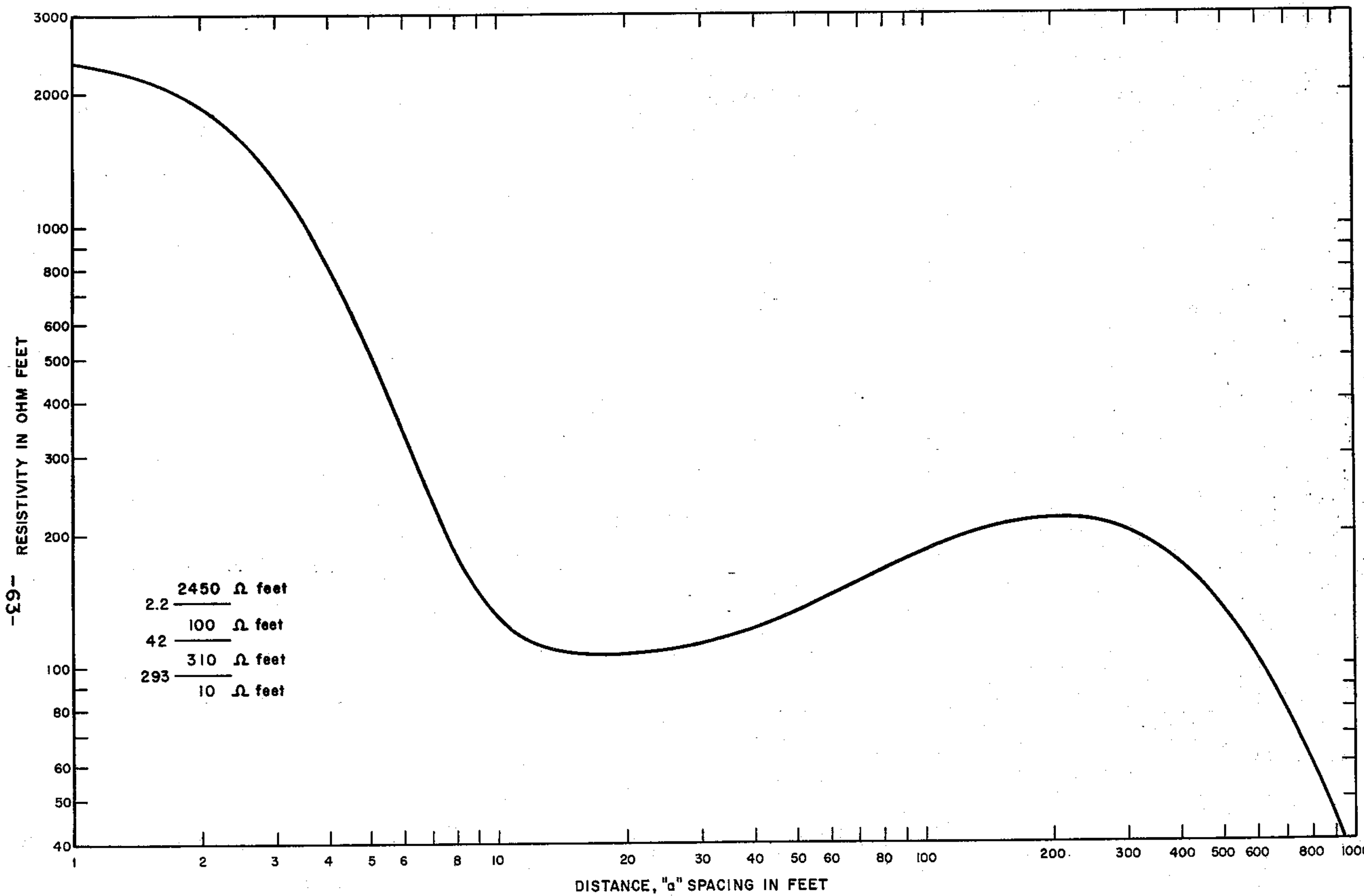


Figure 41 Computer curve of the interpretation of Figure 40 made by the curve matching technique.

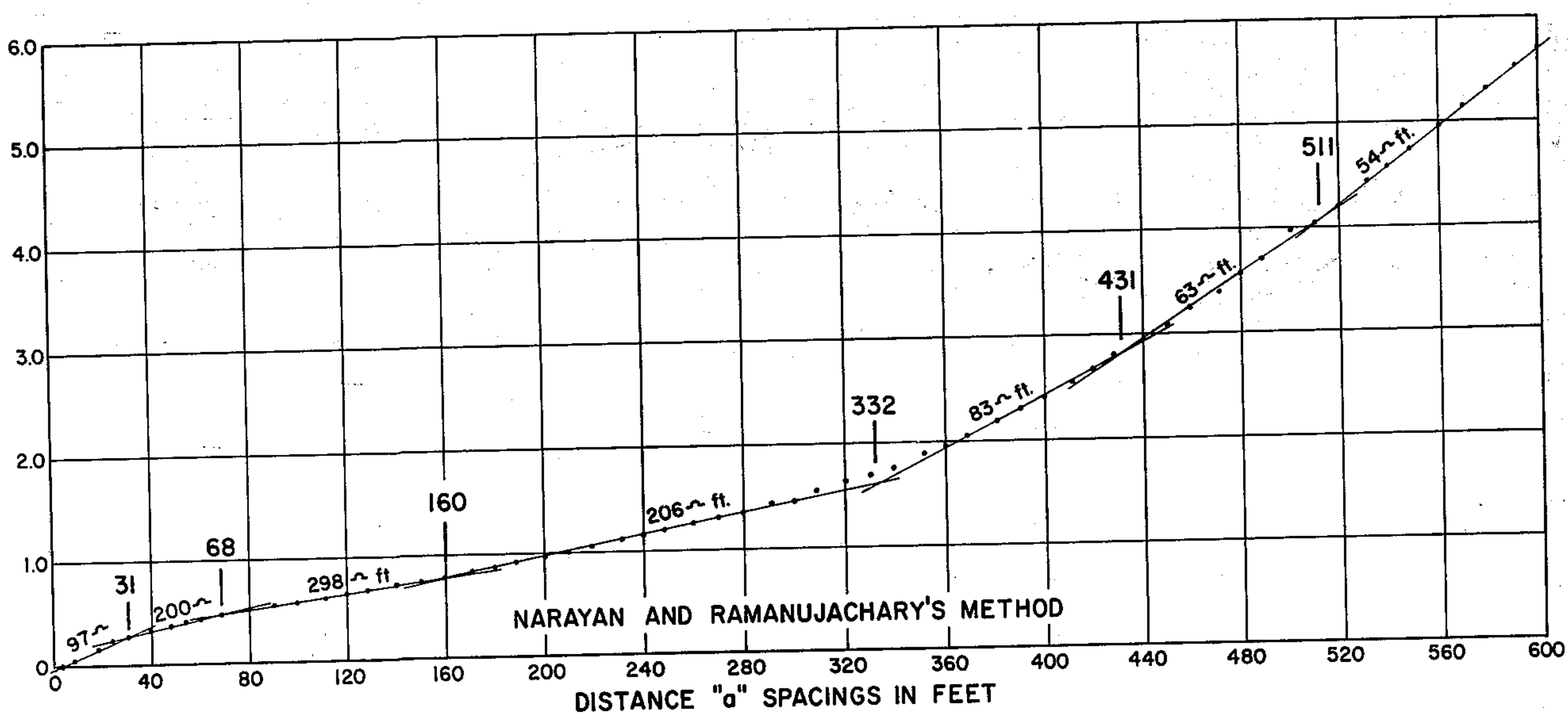


Figure 42 The inverse slope method of interpretation of line 3 from Midway Rest Stop.

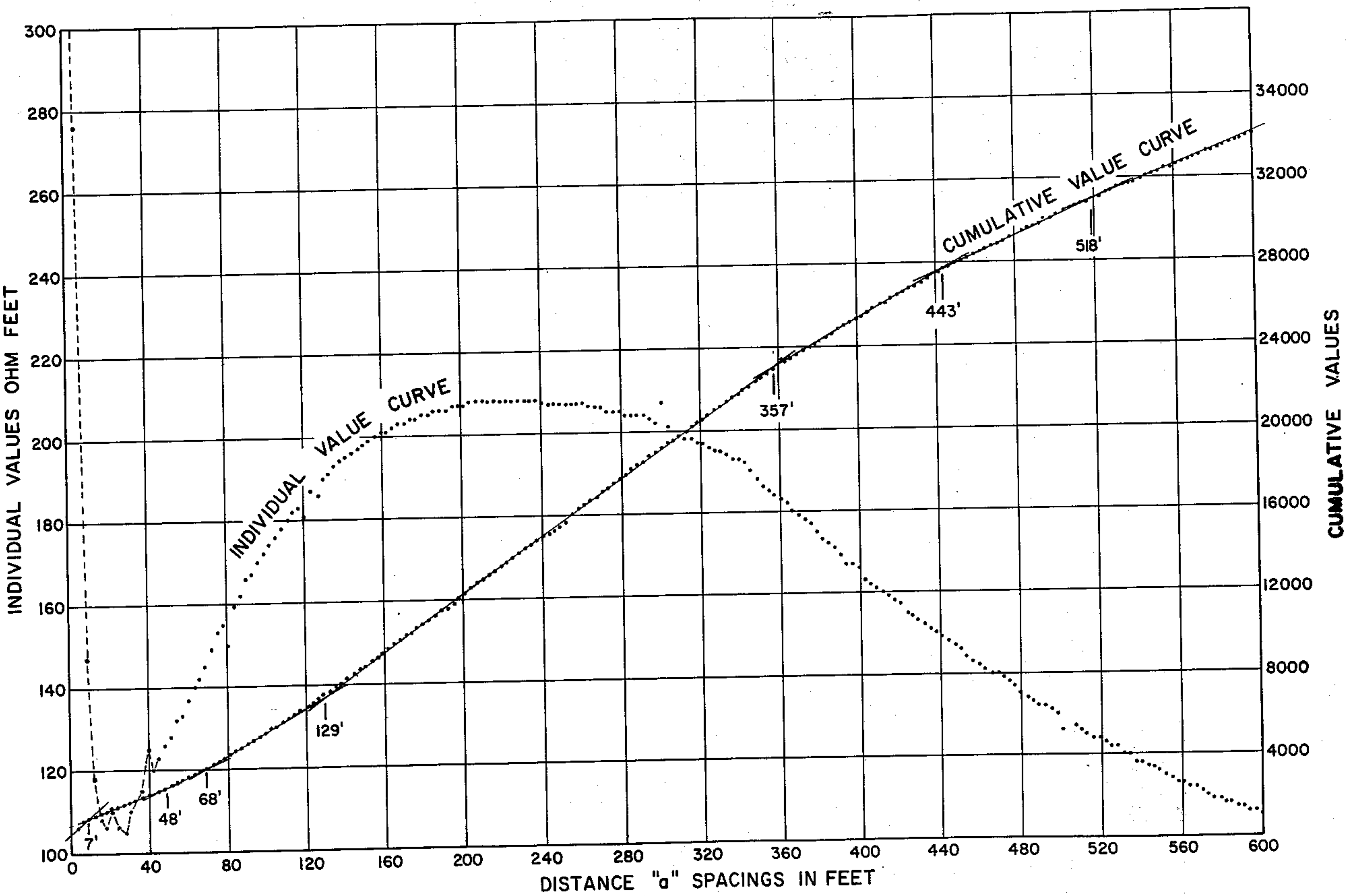


Figure 43 An interpretation of line 3 from Midway Rest Stop by the cumulative method.

Table 2

A comparison of the depths obtained by three different resistivity interpretations with the drill log from the site at Midway Rest Stop.

Curve Matching		Cumulative	N and R Method		Drill Log	
Depth	Resistivity	Depths	Depth	Resistivity	Depth	Material (from composite of drillers log)
	2450Ωft.	7		97Ωft.		
2.2			31		0-75	Mixed sands, some gravels.
		48		200Ωft.		
	100Ωft.	68	68			
		120		298Ωft.	75-190	Sands, gravels
			160			
60				206Ωft.	190-335	Gravel layers, sand & clay layers, producing water from gravel at 269 ft.
		364	332			
				431Ωft.		
	300Ωft.	442	431			
				63Ωft.		
345		531	511			
				54Ωft.	335-501	Clay, sandy clay, some sand and gravel layers.
	10Ωft.					

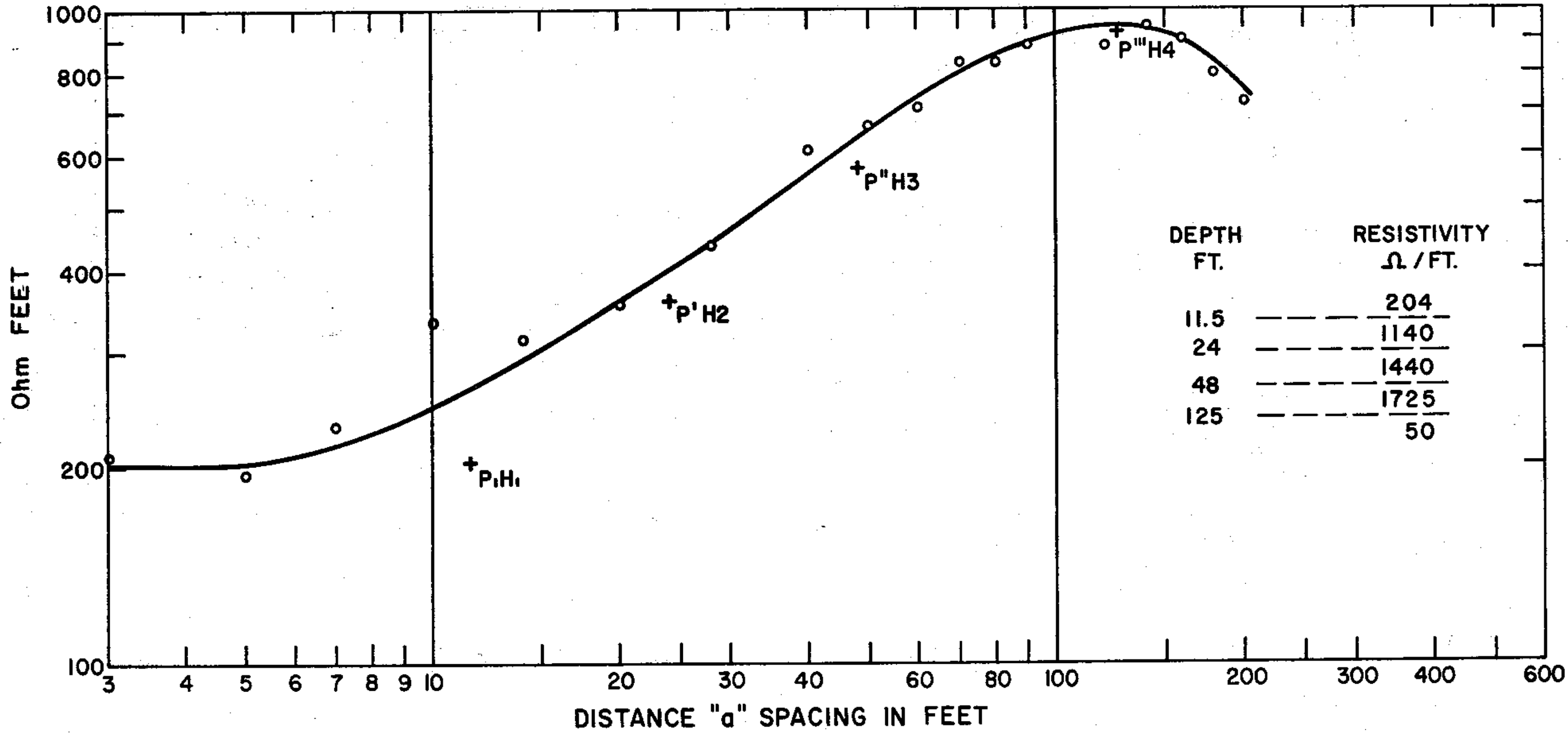


Figure 44 Field resistivity curve of Line I at Sonora. The interpretation shown is by the auxiliary point method of curve matching.

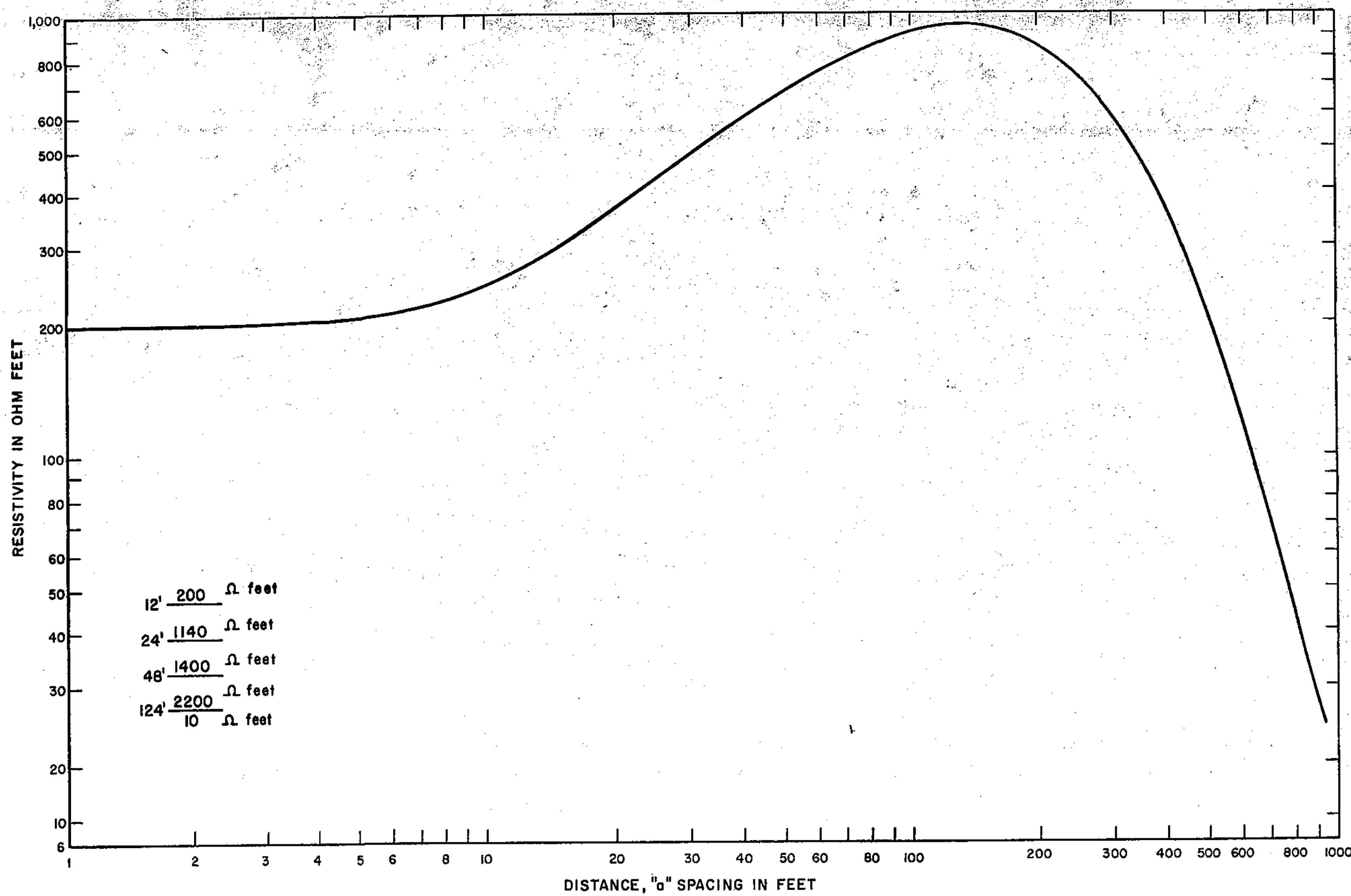


Figure 45 Computer curve of the interpretation of Figure 44 made by the curve matching technique.

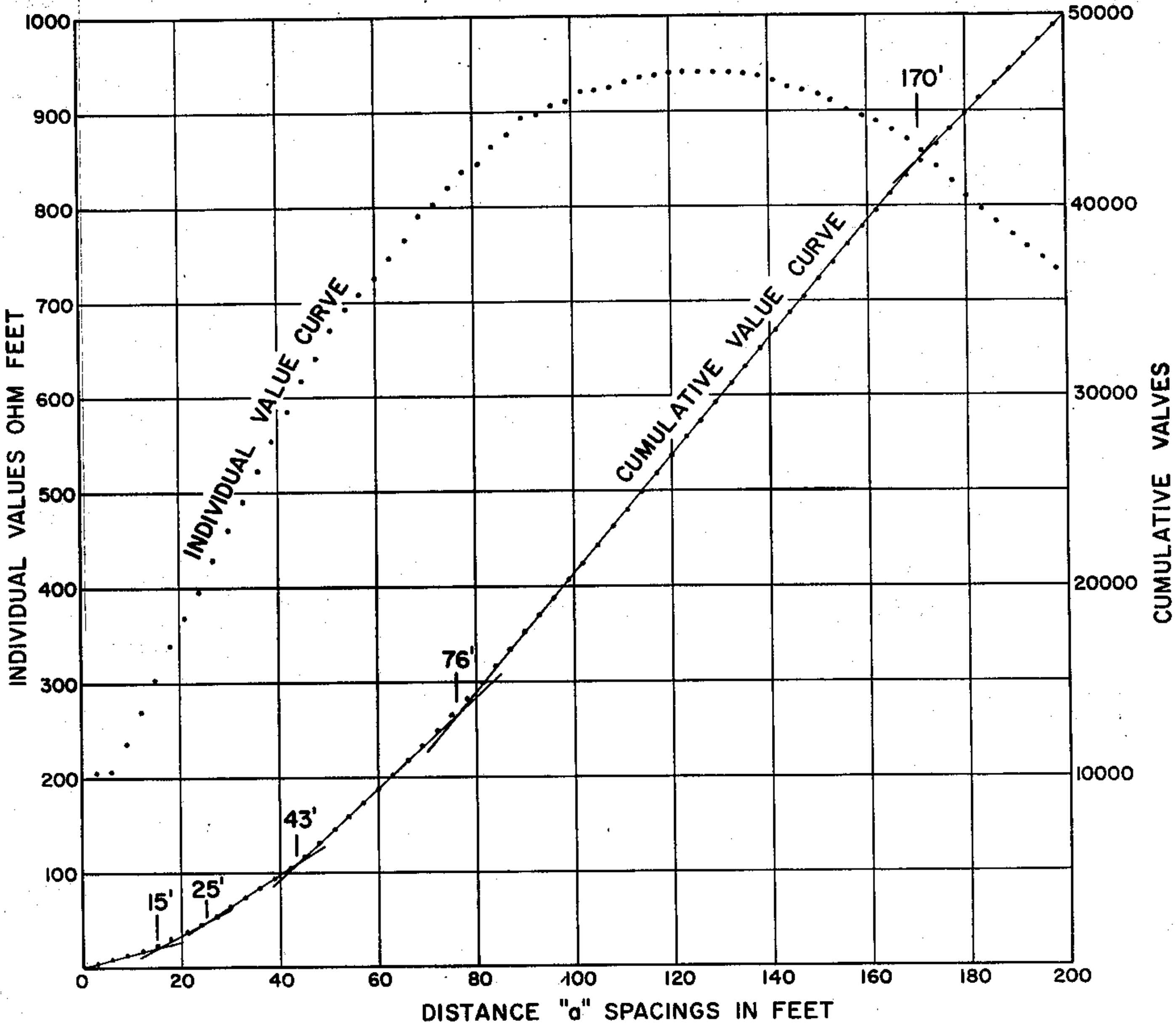


Figure 46 An interpretation of line 1 at Sonora by the cumulative method.

the line on the 10x10 paper will have the apparent error emphasized when plotted on the log log paper. If the curve is smooth on the 10x10 paper, it will also be so on the log log paper with no outliers or sharp inflections.

Data points taken off a smooth curve on log log paper and replotted on 10x10 graph paper, will also form a smooth curve with no sharp inflection points. The cumulative value curve is then a smooth rounded curve with no straight line sections. Completion of the interpretation by the cumulative method then becomes very arbitrary, and subject to operator influence.

On the basis of this study, the curve matching technique is the interpretation method currently used by this department. A computer program has been adapted that verifies the interpretation made by the operator. When master curves cannot be found that are direct matches for the field curve, an auxilliary point method is used to obtain a first approximation. The first approximation is then submitted to the computer for verification. The computer program calculates a curve which fits the interpretation submitted to it, and draws this curve on an XY plotter. The computer curve is then compared with the field curve and any necessary adjustments are made in the interpretation. The new approximation is again submitted to the computer and the new curve is again drawn by the plotter. This procedure is continued until a satisfactory match is achieved.

The number of computer runs is dependent on the quality of the first approximation. Simple situations involving two or three layers are usually resolved in one to three runs. More complicated situations of three or more layers have required up to six runs.

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APPENDIX

Summary of Field Work Performed at Each of the Different Sites

The three resistivity instruments were compared with each other by comparing the results of their use at many different locations involving different conditions of surface resistivity. To facilitate comparison, the following summary was made of the different lines run and the ground conditions at the time the work was performed. A statement is also included which describes the success of the operation.

08-SBd-40 (Mountain Springs)

March 1969. Dry sandy soil overlying meta-igneous rock.
BPR instrument. Performed well on 44 profiles. Collected 5 VES curves that exhibited considerable scatter.

08-SBd-15 (Midway)

January 1972. Dry fine-coarse silty clayey sand.
Bison instrument. Collected 2 VES curves that were good out to "a" spacings of 140 feet, but had considerable scatter beyond that.

February 1972. Same material, but with moisture from about 2 inches below the surface to 12 inches below the surface. Geo-Recon instrument. Repeated one of the above lines with no scatter out to an "a" spacing of 600 feet. Collected 5 other VES curves with no scatter on any of them. Ran 2 profiles using "a" spacings of 400 and 500 feet with no scatter.

08-SBd-15 (Halloran Springs Rest Stop)

November 1970. Dry, fine-coarse granitic sand.
Bison instrument. Ran 3 VES lines, used salt water on the electrodes and still had trouble getting current flow. Data was badly scattered, making interpretation nearly impossible.

Geo-Recon instrument. Ran 2 VES lines, used saltwater on the electrodes and still had low current flow. Data was badly scattered, making interpretation nearly impossible.

January 1971. Same material as above, moisture at a depth of 3-4 inches.
Geo-Recon instrument. Ran 6 VES lines with "a" spacing of 600 feet. There was a very small amount of scatter. No trouble making interpretations.

10-Sol-80 (American Canyon)

April 1970. Moist silty clayey soil.
Bison instrument. Ran 5 VES lines with "a" spacing of up to 100 feet, and 2 Wenner profiles with 20 and 40 foot "a" spacings of from 20 to 80 feet. Beyond these distances interference from some source made the recorded values increase at an unreasonable rate. The profiles were good.

One gradient profile was attempted, using a P_1P_2 distance of 20 feet. The values were too small for the instrument to record.

10-Sol-37 (Mare Island)

August 1970. Wet soft mud.
Bison instrument. A Wenner VES, a Schlumberger VES and a Wenner profile were run. The Wenner VES was run to an "a" spacing of 350 feet. There was a small amount of scatter, but the line was good to an "a" spacing of 90 feet. Beyond 90 feet the curve was rising too steeply. The Schlumberger line was good to about 100 feet, but became too steep beyond that distance. The profile was good except for one reading when the grounding lead was disconnected.

Geo-Recon instrument. A Wenner VES and Schlumberger VES were run at the same location as above. The Wenner had an "a" spacing of 400 and a small amount of scatter. The Schlumberger VES was run to 500 feet and also had a small amount of scatter. The depth determinations of the two Wenner lines agree. The Geo-Recon Schlumberger agrees with the two Wenner lines. The Bison Schlumberger disagrees. The Wenner lines agree with reflection and refraction data.

10-Ama-16 (Tunnel area)

March 11, 1970. Wet sandy clayey soil, sand and clay.
Bison instrument. A gradient profile using P_1P_2 distances of 10 feet was attempted. The recorded values were too small to be reproducible. Two VES lines were run using "a" spacings of up to 200 feet. Both had considerable scatter beyond about 60 feet.

BPR instrument. Three gradient profiles were run using P_1P_2 distances of 10, 20 and 30 feet. There was some trouble with reproducibility on the 10 foot line, the other two were very good.

March 26, 1970. Sandy Clayey soil, sand and clay, dry on the surface, moist at shallow depth.
Bison instrument. Five gradient profiles were run, using P_1P_2

distances of 20 and 30 feet. One 20 foot line was repeated, using dry electrodes and one with water around the electrodes. The contact resistance did not appear to be too great with the dry surface and moisture at depth; but, the dry electrode condition gave results that were erratic in comparison with the wetted electrodes.

BPR instrument. A gradient profile was run along the same line as above. The plotted values are parallel, but the BPR values are much higher. A Wenner profile was run, with good detail and with essentially the same line of plotted values.

April 1970. Dry sandy clay, clay and sand.
Bison instrument. Three Wenner profiles and three gradient profiles were run at the same location. The data appears to be good.

May 1970. Same material, dry on the surface, moist at depth.

Bison instrument. A Wenner profile was run at the same location as in April. The two profiles are nearly parallel and have very similar values.

Geo-Recon instrument. One Wenner profile was run at the same location as above. This profile was parallel to but moderately higher in value than the ones by the Bison. Two Wenner profiles were run which showed good reproducibility and were similar to the others.

10-Tuo-49,108 (Sonora)

March 1971. Wet clay soil overlying limestone.
Bison instrument. Twelve gradient profile lines were run. The data appeared to be good. A wide range of values between adjoining profiles suggests some scatter.

April 1971. Moist clay soil overlying limestone.
Bison instrument. Fourteen gradient array profiles, 26 Wenner profiles and 1 Wenner VES were run at this time. One gradient array was a repeat of one run in March. This line shows some scatter, and higher values of resistivity than were recorded in March. Contouring this data indicated several of the readings were anomalously high or low. The Wenner VES had no scatter.

The Geo-Recon instrument. Three Wenner profiles were run. The data appears good and parallels that recorded with the Bison.

September 1971. Dry clay soil overlying limestone. The area was enlarged to include territory underlain by meta-sediments.
Bison instrument. Nine Wenner profiles, 18 gradient profiles and 3 Wenner VES lines were completed. The gradient profiles

had scatter but were acceptable. The 25 foot Wenner profile had some scatter, but the 75 and 125 foot Wenner profiles had no apparent scatter. One VES line was very good, the other two had considerable scatter.

Two attempts were made to run gradient profiles with P_1P_2 distances of 25 feet. Both were unsuccessful, with values that were not reproducible.

03-Yol-16 (Yolo Bypass)

July 1970. Firm sandy clayey soil, dry at the surface, moist at shallow depth.
Geo-Recon instrument. One Wenner VES line was run. The line was usable but had considerable scatter.

Trans Lab Sacto 1/74 200